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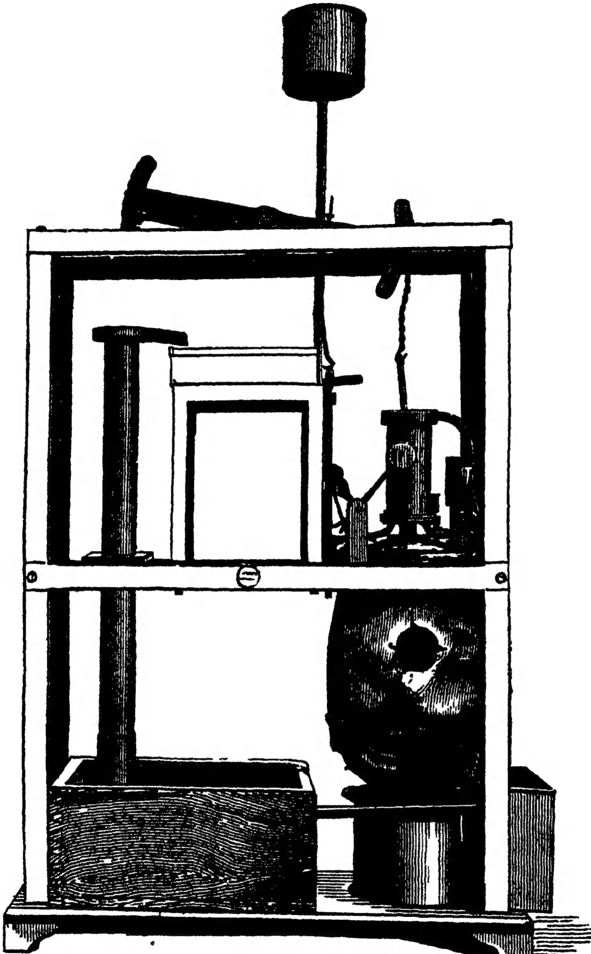

THE GLASGOW MODEL OF NEWCOMEN'S STEAM ENGINE

NOTE.—In working to repair the model here represented, James Watt, in 1765, made the discovery of a separate condenser, which has identified his name with the steam engine

TEXT-BOOK

ON THE

STEAM ENGINE

WITH A SUPPLEMENT ON

GAS ENGINES

BY

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BARRISTER-AT-LAW

PROFESSOR OF MECHANICS AT THE NORMAL SCHOOL OF SCIENCE AND
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PREFACE

TO

THE EIGHTH EDITION.

THE plan of this book is the following:—The first chapter contains a sketch of the steam engine as it existed in the time of Watt, together with an account of the ideas then prevalent as to the nature of heat, and concludes with a summary of some physical properties of steam. The second and third chapters are occupied by an investigation of the principles of the modern theory of heat in its application to the steam engine. Then comes a chapter on the conversion of motion, which deals with certain salient points in the mechanism of an engine. The fifth chapter is mainly devoted to the expansion of steam, to the action of valves, and to the application of Watt's indicator. The sixth chapter treats of boilers and the consumption of fuel. The seventh chapter is on compound cylinder engines, and is illustrated by some drawings of the engines constructed by Messrs. Maudslay, Sons, and Field for the White Star line of mail steamers making the voyage between Liverpool and New York. Finally, there is a chapter on miscellaneous details, such as steam-engine governors, Giffard's injector, the link motion, modern valve gears, and valve diagrams. The part relating to the steam engine contains also an Appendix, with a series of examination questions and answers. There is in the present edition a Supplement on Gas Engines.

T. M. GOODEVE.

5 CROWN OFFICE ROW, TEMPLE.
January, 1887.

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ELEMENTARY TREATISE

ON THE

STEAM-ENGINE.

CHAPTER I.

THE STEAM-ENGINE AS VIEWED UNDER A KNOWLEDGE OF THE DOCTRINE OF LATENT HEAT.

THIS treatise is intended to prepare the way for a complete and extended study both of the theory and practice of the steam-engine. We premise that there is much introductory matter which the student should consider and arrange in his mind before he can hope to grapple successfully with the difficult questions which occur in practice; and the mode of treatment herein adopted is to be taken, not as something sufficient in itself, but rather as an indication of the points wherein existing books on the subject may with advantage be supplemented. The nature of the work will soon become apparent to those who take it as a guide in this particular branch of study.

It is only within the last thirty years that a knowledge of the principles of the mechanical theory of heat has influenced the practice of those who are engaged in improving the construction of the steam-engine, and in seeking to obtain from it a larger amount of useful work with a given expenditure of fuel. The student of mechanics will do well to look backward into the history of scientific discovery, and he should endeavour to trace the progress which has accompanied each successive step in our comprehension of the real nature of that origin of force which we call heat.

Living at the present day, he finds himself face to face with a novel conception, which has struggled into life by slow and almost insensible degrees, but which appears to be accepted with the same degree of confidence as that accorded to Newton's theory of universal gravitation. True it is that the new doctrine, which is recognised under the name of the *dynamical theory of heat*, has not come upon scientific men in the complete and startling manner in which Newton announced his great discovery; but although its development has been gradual, its applications are almost universal, and we are ever finding it a guide to valuable results which would probably have remained undiscovered were it not that a new impulse had been given to our thoughts.

This chapter is devoted to an account of the progress of the steam-engine, under a perception of the doctrine of latent heat, and extends only to the period of Newcomen and Watt, when the statement that heat was a material substance was almost universally accepted as being true. In pursuing still further, through subsequent chapters, the progress of improvement and discovery, we shall gradually develop the application of that mechanical theory which has displaced all others, and has become the foundation on which the whole fabric of physical knowledge is built up.

It appears that in the year 1757 Black commenced a course of lectures in the University of Glasgow, and at that date the accepted opinion on the subject of the liquefaction of any substance (say, for example, ice) by the agency of heat was the following :—

A certain quantity of heat being competent to raise the temperature of a mass of ice from 31° F. to 32° F., the same quantity of heat would be competent to melt the ice completely and to produce an equal weight of water at 33° F. In other words, the rise of the thermometer revealed the entrance of heat into the melting body, and gave an exact measure of the quantity so entering and combining with its substance.

This was the statement propounded in the schools at the time referred to; and, in respect of congelation, it was supposed that the inverse process was a simple undoing of that which had been done before, whereby water lost no more heat when passing into ice than that indicated by the fall of the thermometer.

Black was, however of opinion that when a solid substance,

such as ice, changed into a liquid, it received a much greater quantity of heat than that perceptible immediately afterwards by the application of a thermometer; and he performed an experiment which not only established his conclusion, but also gave him a measure of the excess of heat required to cause liquefaction in a solid substance.

BLACK'S DOCTRINE OF LATENT HEAT.

The object being to estimate the amount of absorption of heat into melting ice, and the concealment of it in water, Black selected two thin globular glasses, A and B, each about 4 inches in diameter, and very nearly of the same weight. Into A he poured 5 ounces of pure water, which he congealed by a freezing mixture of snow and salt, and after allowing the glass to stand for a few minutes until the ice inside was beginning to melt and the temperature of the surface had risen (*in his estimation*) to 33° F., he suspended A by a slender wire in a large empty hall, the air of which remained at a uniform temperature of about 47° F. throughout the experiment.

In like manner he poured into B exactly 5 ounces of water previously cooled as nearly as possible to 33° F., and after placing a very delicate thermometer therein, he suspended this latter vessel at a distance of 18 inches from A.

At the end of one half-hour the water in B rose to 40° F., but it was not until a lapse of ten and a half hours that the water in A arrived at the same temperature, and that the whole of the ice became practically melted, the residue being a very small spongy mass which was disregarded.

Black reasoned, according to the scientific language of that day, somewhat as follows:—The external heat is entering the water-glass with a certain celerity whereby it has received $40-33$ or 7 degrees of heat in one half-hour; the external heat is entering the ice-glass under similar circumstances, and the heat received by the ice-glass in twenty-one half-hours is $21 \times (40-33)$ or 147 degrees. This is a quantity of heat which, had it been added to the liquid water, would have directly raised its temperature by a corresponding amount. No part of this heat, however, appears in the water except, at the utmost, $40-32$ or 8 degrees, and the inference is

that the remaining 139 or 140 degrees have been absorbed by the melting ice and are concealed in the water into which it has been changed.

The expression 'a degree of heat' was here used as meaning that which is properly called a '*unit of heat*,' and which cannot be defined until the theory of heat is explained. The student will find the whole matter set forth in the second chapter; at present he should regard heat as something measurable as to *quantity*, although not a material substance, a thing apparently impossible at first sight, but hereafter shown to be entirely reasonable. At this stage he should be careful to avoid the use of the word 'degree' except as applied to temperature. As a general rule, it is wrong to estimate quantities of heat by degrees of temperature.

For a definition of temperature we refer to Mr. Maxwell.

DEF :—The *temperature* of a body is its thermal state considered with reference to its power of communicating heat to other bodies.

For a definition of latent heat take the following :—

DEF :—*Latent heat* is the quantity of heat which must be communicated to a body in one given state in order to convert it into another state without changing its temperature.

In like manner it was taken for granted that after a body is heated up to its *vaporific* point, nothing further was necessary than the addition of a little more heat in order to change it into vapour, but Black disproved this notion by a series of experiments, whereof one is recorded as having been made on October 4, 1762.

Into each of two flat-bottomed tin-plate vessels, about 4 or 5 inches in diameter, he poured the same quantity of water at a temperature of 50°. The vessels were placed on an iron plate, nearly red-hot, under which a fire was burning, and the water in each began to boil after an interval of four minutes. In twenty minutes more the whole of the water had boiled away; and since it had gained (in the imperfect language of that day) 162 degrees in the first four minutes, or $40\frac{1}{2}$ degrees in one minute, and since the temperature of the steam was no higher than that of the boiling water, the experiment showed that $20 \times 40\frac{1}{2}$ or 810 degrees of heat had been absorbed by the water and carried off by the steam. This result is not accurate, for the sources of error are numerous, but

the experiment induced more careful investigation, and it is now generally taken that 966·6 *units of heat* become latent when one pound of boiling water is converted into steam.

Another illustration is thus described by Black:—

'I have put a lump of ice into an equal quantity of water heated to the temperature of 176° F., and the result was that the fluid was no hotter than water just ready to freeze.'

Assuming this to mean that the ice in melting cools the hot water down to a temperature of 33° F., we should have 176−33 or 143 as the number of units of heat on the Fahrenheit scale which became latent during the liquefaction of one pound of ice at 32° F. This number expresses the latent heat of liquefaction in the case of ice.

Even at the present day the writers on heat are not in agreement as to the measure of the latent heat of the liquefaction of ice. Tyndall assigns the number 143, Balfour Stewart adopts 142, and Maxwell 144, as the number of units of heat on the Fahrenheit scale which become latent in the passage of 1 lb of ice at 32° F. into water at the same temperature.

It appears, therefore, that heat becomes latent when a substance undergoes a change of consistence, that is, when it passes from a solid into a liquid state, or from a liquid state into one of vapour. Hence we speak of the latent heat of fusion, and of the latent heat of evaporation. But heat disappears under other conditions, as will be explained, and accordingly it becomes necessary to refer to the disappearance of heat during expansion as well as during certain chemical changes. The doctrine of latent heat, so far as it is material at present, relates only to the cases of liquefaction and evaporation.

THEORY OF HEAT AT THE TIME OF BLACK.

In order to prepare the way for the first great discovery in the steam-engine, we should carefully consider the view which Black himself entertained as to the nature of this thing called heat which became latent during the conversion of ice into water or of water into steam.

To us, at the present day, while profiting by the light of the

knowledge everywhere existing, it seems incredible that anyone who thought on the subject could have seriously entertained any doubt but that something capable of being measured as to its quantity was really passing from the furnace into the boiler of an engine during the whole time that the water was being converted into steam. Any such erroneous notion as the measurement of quantities of heat by a thermometer was swept away at once and for ever by Black's experiments; but nevertheless it is a remarkable thing to find that the very men who became the leaders in a new advance of scientific research should have embraced theoretical views as to the agency of heat which in their turn barred the way to all true progress.

The doctrine of latent heat was made transparently clear by the facts just referred to, but the question as to what heat really was received a most unsatisfactory solution. For the present purpose it is unnecessary to refer to the arguments by which the so-called *material theory of heat*, or the doctrine of *caloric*, was supported.

It may here suffice to state the view entertained by Black and those who followed in his steps, viz., that *heat is a subtle elastic fluid* termed *caloric*, which surrounds, as by an atmosphere, the grosser particles of all material bodies; the atoms of caloric being so much smaller than those of matter, that each material particle may be conceived to be surrounded by a large number of them. Further, the atoms of caloric have a strong repulsion for each other at the same time that they attract the particles of matter.

In other words, heat is an indestructible, elastic, gaseous fluid, which weighs nothing, which insinuates itself into the pores of bodies, causing them to expand and dilate, which combines with bodies so as to become latent when they pass from a solid to a liquid state, or from a liquid into a vapour, and which reappears when the passage is reversed. Just as certain gases are absorbed and become fixed in bodies, so this subtle fluid of heat enters into every form of matter, and causes repulsion by reason of the property that its own particles are self-repulsive and not attractive. In this way the repulsion due to the heat fluid separates the particles of ice till it becomes water, and still further drives asunder the particles of water till it passes off as steam or vapour.

At the time of Watt, when the advantage of using high-pressure steam came to be discussed, the absorption of heat in generating steam was thus regarded, and it was said: 'Highly elastic steam requires as much more heat for its formation as it is more elastic; for it is, in fact, only a greater quantity of heat and water crowded into a smaller space. Hence, any greater power that it possesses will be obtained by a proportionately greater expenditure of heat.'

The conception that heat was a fluid received all possible adornment at the hands of mathematicians, as in Kelland's theory of heat, A.D. 1837, which was a text-book at Cambridge down to the year 1849, or even later. In this work the statement on the first page is that 'the popular (probably the correct) idea attached to heat or caloric is that of a subtle fluid emanating from hot bodies and entering between the particles of colder ones.'

SAVERY'S ENGINE.

ART. 1. We pass on to review the invention of steam-engines as preceding and accompanying the discovery of the doctrine of latent heat, and we prefer to begin with an account of the invention of a steam-engine which was the subject of letters patent, bearing date July 25, 1698, and granted to Thomas Savery. An account of this 'engine to raise water by fire' was set forth by the inventor in a treatise called 'The Miner's Friend.' A cheap reprint of the paper, together with facsimile copies of Savery's drawings, can be obtained at the Patent Office.

In a letter addressed to the 'Gentlemen Adventurers in the Mines of England' the patentee says that he should never have pretended to any invention by the old causes of motion, but that he 'had happily found out this new, but yet much stronger and cheaper, force or cause of motion than any before made use of.' Then he points out the advantages of the new method, and makes one observation which gives an idea of mechanical construction at that time: 'As for pump-making, that part of the trade will be much improved by my engine, for I must use board and timber for pipes, and have considerable employment for pump makers and carpenters for timber used about my engine. . . . For my design is not in the least to prejudice the artificers, or, indeed, any other

sort of people by this invention, which on the contrary is intended for the benefit and advantage of mankind in general.'

Coming after the discovery of the law of atmospheric pressure, Savery's engine was based on the principle of the barometer, the action being that water was forced upwards into an empty receiver by atmospheric pressure, and was afterwards carried to an additional height by the pressure of steam.

The arrangement and operation of its working parts will be understood from an inspection of fig. 1, which is a diagram showing the principle of the engine without giving the details of its construction. Steam is generated in a boiler A, and passes into a receiver B, which communicates with a pipe H K leading from some water below the level of the apparatus to a reservoir overhead. At E and D are two clack valves, each opening upwards, and F is a tap for throwing cold water on the receiver.

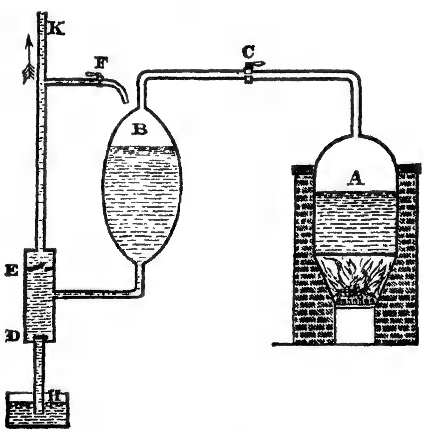


FIG. 1.

The action is the following :—The stopcock C, which admits steam from the boiler into the receiver, is opened, and the rush of steam expels the air from B by driving it upwards through E. Then F is opened and C closed, while a jet of cold water is allowed to play upon the outside of B, thereby condensing the steam to a great extent and lowering the pressure of the vapour in B. The

pressure of the external air at H presently forces a quantity of water up the pipe H and through the valve D, whereby the receiver becomes nearly filled with water. Steam is again admitted into the receiver and forces out its contents through the valve E. The tap F is opened with the same result as before, and the action is renewed. A drawing which shows the general appearance of the engine and the mode of applying it to the draining of a mine, is to be found in 'The Miner's Friend.' There are two receivers, each similar to B, the object being to force water out of one vessel while the other is being filled, and thus to render the flow continuous. The boilers and receivers stand upon a stage which appears to be some 20 or 25 feet above the level of the water, while the height of the overflow may be 30 or 40 feet above the boilers.

A trial of Savery's engine, as made at Manchester in 1774, is recorded by Smeaton.

The receiver was a cylinder, 2 feet in diameter and 7 feet high. The engine delivered water at a height of 19 feet above the surface of a well, and made 7¼ strokes per minute, each stroke filling the receiver to a height of 6 feet. The work done was the raising of 18¾ cubic feet of water per stroke through a height of 19 feet, which was equivalent to raising 136 cubic feet per minute to the same height. The consumption of coal was 32 cwt. in 24 hours, or about 1¾ bushels of 84 lbs. per hour. Each bushel of coals would therefore raise about 5½ millions of pounds through one foot. This is less than one-tenth part of the work performed by a modern pumping-engine.

The loss of heat was enormous. First, there was the condensation of a quantity of steam, consequent upon its coming in contact with the cold water about to be driven out by it. No doubt this action would speedily come to an end, because a layer at a boiling temperature would form upon the surface, and the bad conducting power of water would prevent this layer from extending to any depth, but in the mean time a considerable waste of heat took place. And secondly, during the expulsion of the contents of the receiver additional surfaces of cold metal would be continually presented which would cause condensation, the heat so absorbed being entirely wasted. The principal defect, namely, the alternate heating and cooling of the receiver, remained

uncorrected and clung to the engine through all subsequent stages of modification and improvement until the invention of a separate condenser in the year 1769.

THE PRESSURE OF STEAM FROM WATER BOILING IN THE OPEN AIR IS EQUAL TO THE PRESSURE OF THE ATMOSPHERE.

2. There are many simple experiments for showing that the pressure of steam from water boiling in an open vessel is equal to the pressure of the atmosphere.

1.—A cylindrical vessel with flat ends, made of tin-plate, say 5 inches in diameter and 10 inches long, has a stopcock fitted at the top. A small quantity of water is poured into the cylinder, and made to boil by the heat of a lamp. As soon as steam issues freely from the stopcock, the tap is closed and the vessel is exposed to a jet of cold water; this condenses the steam, whereby a partial vacuum is formed within the vessel, and the atmospheric pressure causes its sides to collapse and to flatten together with considerable violence.

The explanation is that the steam displaces and drives out the air—just as it cleared the air from the receiver B in the Savery engine—but supplies a pressure undistinguishable from that of the atmosphere, which pressure continues until condensation takes place.

2.—Another experiment, very easy of performance, gives the young student an insight into some fundamental properties of steam.

A glass flask, A, about 4 inches in diameter, is partly filled with water and placed over the flame of a lamp. C D is a bent glass tube, one leg of which is open and passes through a cork in the neck of the vessel, while the other terminates in a fine orifice and dips into a beaker of cold water.

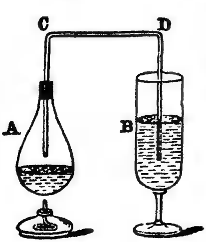


FIG. 2.

First, let the open end of the tube in A be raised above the level of the water.

On applying heat, bubbles of air continue to escape into B; this shows the expansion of air by heat as well as the displacement of it by the vapour of

water. The bubbling of the air in B goes on until the water has been boiling some little time, the steam which is carried over with the air being condensed in the tube itself; but presently no more air escapes and a loud cracking noise indicates the escape and condensation of the steam at the orifice.

The next thing to be noticed is the rise of temperature of the water in B. It may easily be arranged that the water in B shall be caused to boil by the condensation of the issuing steam, and then we have the water boiling in both vessels. This result was observed by Watt and caused him to consult with his friend Dr. Black as to the correct explanation of it.

Secondly, press the tube further into A until the end dips below the level of the water, and remove the beaker. It will now be seen that the water rises up the tube and begins to travel along C D. By withdrawing the lamp and again applying it, the end of the column of water may be made to move to and fro along C D, thereby indicating the delicacy of balance between the pressure of the steam in A and the pressure of the atmosphere outside the vessel.

Finally, replace the beaker, and the water can be passed from B to A or from A to B at pleasure.

SAVERY'S ENGINE INADEQUATE FOR DRAINING MINES.

3. In considering the practical working of Savery's engine it is necessary to remember that although water could be raised through a height of 20 feet or thereabouts into the receiver by simple atmospheric pressure, there would still remain the task of forcing it to the top of the mine, and for this purpose a supply of steam would be required at a pressure proportionate to the height of the column of water lifted, every additional 33 feet of water demanding an increased pressure of 15 lbs. on the square inch, which again would require to be supplemented to the amount of 3 or 4 lbs. in the boiler in order to overcome loss by cooling, condensation, and friction.

The main obstacle to the application of the apparatus on a large scale would be found in the boiler. How was a vessel to be constructed which should support with safety an internal burst-

ing pressure some two or three times greater than that of the atmosphere? The practical difficulties connected with the construction and form of boilers will be discussed in a separate chapter, and here it may suffice to refer to Mr. Bramwell ('Lectures on the Steam-Engine'), who remarks :—'It is by no means surprising that the mechanical skill and appliances of that time were unable to cope with the demands made upon them, and that pipes, joints, and cocks leaked and gave way,' whereby it became impossible to make a good working engine for mines.

A pumping apparatus on Savery's principle was thus inadequate to the wants of mining engineers, and the problem of adapting the power of steam to the lifting of water through considerable heights yet remained open for solution. It was speedily mastered by the inventive genius of Newcomen, whose engine, improved and altered and remodelled by Watt, has yet remained to the present day as the representative type of a single-acting pumping engine.

NEWCOMEN'S INVENTION OF THE ATMOSPHERIC ENGINE.

4. It appears that about the year 1710, Thomas Newcomen, ironmonger, and John Cawley, glazier, of Dartmouth, in the county of Devonshire (whose names are associated as the makers of the first engine which worked a pump), made several experiments in private, and in the year 1712 put up at Wolverhampton an engine which acted successfully. The progress made was very rapid, and it is recorded that in the year 1737 there was a pumping engine of the Newcomen construction working a succession of pumps each 7 inches in diameter and 24 feet apart, and making 6 feet strokes at the rate of 15 per minute, whereby water was pumped from cistern to cistern throughout the whole length of a shaft 267 feet deep, by steam at or near the atmospheric pressure. Nothing can show more clearly the remarkable character of Newcomen's invention than a statement of these numbers, but it remains to set forth the exact principle as discovered and applied.

It would seem that improvements connected with the steam-engine have followed closely upon those made in connection with enquiries into the nature and properties of air. As pointed out by Mr. Scott Russell in his excellent work on the steam-engine,

Savery's idea was nothing more than an application of the discovery of the law of atmospheric pressure; and in like manner Newcomen might well have been a pupil of Otto von Guericke, and might have claimed merely to have put to a practical use one of the earliest experiments on the power of an air-pump. As a matter of fact it is very probable that Newcomen worked out the problem quite independently of any previous knowledge of what had been done by Otto von Guericke, but in collating the history of inventions it is impossible to lose sight of the various steps made in one common direction. The most striking early experiment with the air-pump was the cohesion of two hemispheres known as the Magdeburg hemispheres, but there was another illustration nearly as remarkable, which was the following:—

A vessel of copper made truly cylindrical was fitted with a piston 8 inches in diameter, which allowed no air to leak round it. The piston was attached to a rope passing over a pulley above the cylinder and carried on one side so as to run over a second pulley before being attached to a heavy weight. When the trial began the weight was on the ground, and the piston was at the top of the cylinder. A boy then pumped out the air from the bottom of the cylinder by means of an air-pump, and the result was that the pressure of the external atmosphere on the movable piston forced it down and lifted the weight.

The work here done by the air-pump could be accomplished equally well by steam. The exhaustion of the cylinder might be effected by a jet of steam, which would displace the air within, and supply a pressure equal to that of the atmosphere. Upon condensing the steam the cylinder would be exhausted even more completely than by the mechanical action of an air-pump, and the piston would be forced down just as in the previous experiment.

Instead, however, of lifting a weight by a chain passing over a pulley, Newcomen employed a beam and gave us the type of modern beam engines. The object in view was to pump water out of a mine, and the arrangement for doing it was to hang the pump rods at one end of a strong beam centred on its middle point, and to hang the piston of a steam cylinder at the other end of the beam. The condensation of steam in the space below the piston produced a vacuum, and the piston was forced downwards

by the pressure of the atmosphere. The descent of the piston at one end of the beam caused the rise of the pump rods at the other end, and thus the atmosphere was continually exerting a mighty force in pulling down one end of the beam against the drag of the pump rods. As soon as steam was readmitted under the piston the pressures on its upper and under surfaces were balanced, whereby the weight of the pump rods caused them to descend and carried the piston to the top of the cylinder. This was the general plan of the engine, and it is said that a beam was indispensable, for there was at that time no special machinery for boring out cylinders, and the packing of a piston so as to make it steam-tight was most easily effected by a layer of water lying on the top thereof. In order to use this water-packing the cylinder was of necessity vertical, and the pumps did their work as the piston descended. It will be seen that the leakage would be trifling during the ascent of the piston, at which time the pressure of the steam balanced that of the atmosphere, and that on the descent of the piston or during the condensation, the leakage might be considerable, but it would do no harm but rather good, as the water passing into the cylinder would help to condense the steam. A story is told to the effect that in putting up his first engine, Newcomen intended to condense the steam by dashing cold water on the outside of the cylinder, and was surprised to find the engine make several strokes and very quick together; on searching he found that the piston leaked so much as to allow a quantity of cold water to pass to the inside of the cylinder, and thereby to condense the steam. This led to the use of a jet condenser as it is called, that is, a jet of cold water thrown in a spray into the interior of the cylinder itself.

DESCRIPTION OF NEWCOMEN'S ENGINE.

5. The general arrangement of Newcomen's engine is shown in the diagram. A piston P, movable in the steam cylinder A, was attached by a chain to one segmental end of the working beam, the pump rods R being hung by a chain at the other end. The boiler B was directly under the cylinder, and a plate or regulator valve K admitted the steam thereto. Towards the

bottom of the cylinder was a small pipe terminating in a clack valve D, called a snifting valve, which opened upwards. A pipe E F leading to a cistern of water overhead was fitted with an injection-cock E, and there was an eduction or waste pipe L M terminating in a small cistern, and having at its end a clack valve M immersed in water and opening upwards. The drawing also

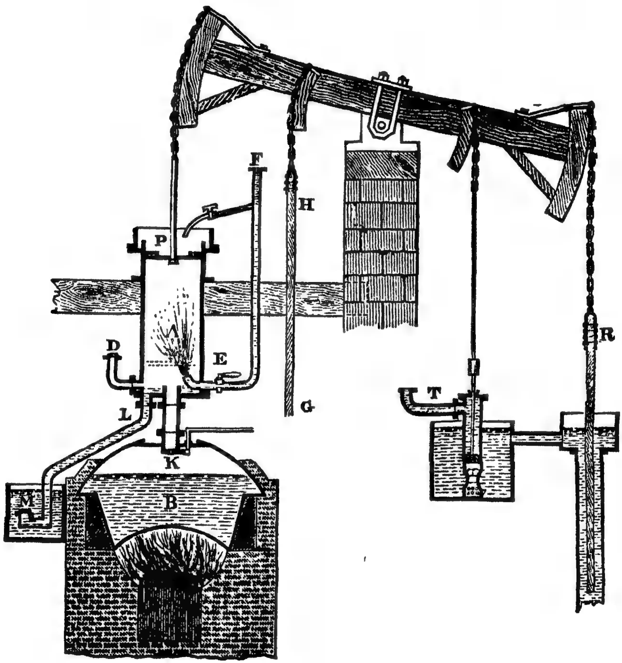


FIG. 3.

shows a vertical rod H G, called a plug rod, which was employed for working the valves, but no attempt is made to indicate the manner in which the connections were made. There was also a small pump T which raised water into the cistern above F, the pipe connecting T with the cistern not being shown.

The weight of the pump rods was greater than that of the piston, and acted as a counterpoise to keep it at the top of the

cylinder unless brought down by external pressure. In order to work the engine, the pressure of the steam in the boiler should be at least 1 lb. per square inch in excess of that of the atmosphere, and the reservoir should be several feet (usually 10 to 12) above the bottom of the cylinder, whereby a strong jet of injection water would be thrown in. The piston being, as above stated, at the top of the cylinder, the steam regulator K was opened and the entering steam cleared out all air from the space A, and drove it through the valve D. The injection-cock E was then opened, whereby the injection water entered the cylinder, slowly at first, but with great force afterwards, as the condensation went on and the pressure of the enclosed vapour was reduced to $\frac{1}{2}$ or $\frac{1}{3}$ that of the air outside. The injection-cock was provided with a hammer weight to ensure its opening quickly. The condensation of the steam took away the pressure from the lower surface of the piston, and there being nothing to balance the pressure of the atmosphere on its upper surface, the piston descended and lifted the pump rods together with the column of water resting upon the buckets. In this way the down stroke of the piston, technically called the '*indoor stroke*,' was completed.

The ascent of the piston in making the return or '*outdoor*' stroke was effected by closing the injection-cock E, and opening the regulator K so as to admit a fresh supply of steam. The waste injection water at the bottom of the cylinder would cause some loss of the entering steam, but it would soon be expelled through the eduction pipe. The pressure on the lower surface of the piston would be at first a little greater, and afterwards about equal to that of the atmosphere, and hence the weight of the pump rods would carry the piston to the top of the cylinder. The injection-cock would then be opened and the action would go on as before.

6. The following example of the working of a small Newcomen's engine is given by Farey, and demonstrates its superiority over Savery's contrivance. It is said that the original engine put up at Wolverhampton had a cylinder 23 inches in diameter with a 6 feet stroke, and made 15 strokes per minute when worked by hand, or 12 strokes when made self-acting, and the dimensions now about to be given are nearly identical with these.

EXAMPLE.—Diameter of cylinder = 24 inches, area = 452 square inches.

Pressure of atmosphere = $14\frac{3}{4}$ lbs.

Pressure of residual vapour in cylinder at temperature of 140° F. to 160° F. = 4 lbs. suppose.

$\therefore$ effective pressure on piston = $10\frac{3}{4}$ lbs.

Here the pump was of 8-inch bore, and the lift 54 yards in perpendicular height, whence weight of column of water = 3,535 lbs.

Taking the pressure on piston at 7·8 lbs., we have $452 \times 7{\cdot}8 = 3{,}525$, and therefore a pressure of 7·8 lbs. will about balance the weight of the water lifted, leaving the difference to raise the counterpoise and overcome the friction of the engine.

Let the stroke of the piston be 5 feet, and the number of strokes 15 per minute.

$\therefore$ Work done = 3535×75 foot-pounds = 265,125 foot-pounds.

Adopting Watt's estimate that a horse can raise 33,000 lbs. through one foot in one minute, we have the horse-power of the engine

$$= \frac{265{,}125}{33{,}000} = 8 \text{ nearly.}$$

Also the quantity of water raised per minute is equal to 26·1 cubic feet, which is 1,566 cubic feet per hour.

7. A singular fact is observed in the working of the engine, namely, that at the beginning of the 'indoor' stroke the cylinder is heaved upwards with a jerk. In a large engine the weight of the cylinder will not counterpoise this upward action, and accordingly massive beams are built into the wall of the engine-house in order to hold the cylinder securely in position.

The lifting of the cylinder is caused by the immediate condensation of steam when the injection water is first admitted, and affords a remarkable illustration of the rapidity with which the steam loses its elastic force in the presence of a colder body. The pressure is instantaneously relieved, but there is a small interval of time, probably from $\frac{1}{3}$ to $\frac{1}{2}$ a second, before the inertia of the pump rods and of the water column is overcome, and the piston begins to move. During that interval the pressure of the atmosphere on the piston and on the base of the cylinder tends to bring them together, and whichever can move first will do so.

Usually it is the piston which moves, but during the small interval while the piston is held immovable by the inertia of the pump rods, the cylinder would be pressed up to meet the piston unless it were restrained, and hence the necessity of the precaution referred to.

As regards the height of the cistern for the supply of injection water, it was usually 12 feet for an engine of 6 feet stroke, but was raised, in some of the largest engines, to 24 or 36 feet.

8. The construction of the Newcomen engine was greatly improved by Smeaton, who designed and erected an engine for the Chase-Water mine, in Cornwall, which had a cylinder of 72 inches in diameter, with a 9 feet stroke, and worked up to 76 horse-power.

The whole structure was on an unexampled scale at that time, and it may be interesting to point to one or two matters of detail. Thus the cylinder weighed 4 tons 16 cwt., and was 10½ feet long. The piston was in the form of a flat circular dish 66 inches in diameter and 1½ inch thick, the edge of the dish being raised so as to form a vertical rim 5 inches high. Underneath the iron dish was a planking of wood 2¼ inches thick, bolted on by a number of bolts, and forming the actual steamtight packing. The planking was surrounded by a hoop of iron ½ inch thick and 2¼ inches broad. There were three columns of pumps, each 16¾ inches in diameter, and 17 fathoms in length, making a total lift of 51 fathoms. The weight of the column of water in the pumps was estimated at 14 tons. The load on the piston was 7¾ lbs. per square inch. The great beam was 27 feet in length, and was made up by bolting together 20 balks of timber, the four nearest the central line being 12 inches square, and the remainder being 6 by 12 inches. There were three boilers, each 15 feet in diameter.

This was the last effort on a system then about to pass away. The engine was set up in 1775, no less than six years after the date of Watt's patent; and we are told that 'when erected it was the most powerful machine in existence. It worked for a few years, and was then altered by Mr. Watt to his improved system, which soon after superseded all the atmospheric engines in Cornwall, where fuel is very expensive, and the mines very deep.'

WATT'S EXPERIMENTS WHILE REPAIRING THE GLASGOW MODEL

9. It now becomes necessary to enter upon a brief account of the great invention connected with the steam engine, and in doing so it may be convenient to refer to the illustration in the frontispiece. The engraving is from a photograph showing the present condition of the celebrated model of Newcomen's engine, which forms one of the principal mechanical treasures preserved in Scotland, and which was exhibited at South Kensington in the Loan Collection of 1876, with the following label attached to it :—'In 1765, James Watt, in working to repair this model belonging to the Natural Philosophy class in the University of Glasgow, made the discovery of a separate condenser which has identified his name with the steam-engine.'

We have an account of the progress of the discovery to which the mind of Watt was now directed in the language of the inventor himself, and a very brief abstract is here given, partly in his own words. Watt says :—'I set about repairing the engine as a mere mechanician, and when that was done and it was set to work, I was surprised to find that the boiler could not supply it with steam, though apparently quite large enough; the cylinder of the model being 2 inches in diameter and 6 inches stroke, and the boiler about 9 inches in diameter.'

Such small models of engines often work very indifferently, and Watt's next observation was that the engine required an enormous quantity of injection water, though but lightly loaded by the column of water in the pump.

He considered that the waste of steam was caused by the fact that the little cylinder exposed a greater surface for condensation in proportion to its contents than would be found in the cylinder of a large engine. Then he thought that 'the cylinder of the model, being of brass, would conduct heat much better than the cast-iron cylinders of large engines (generally covered on the inside with a strong crust), and that considerable advantage could be gained by making the cylinders of some substance that would receive and give out heat slowly.'

He next tried a wooden cylinder, well soaked in oil and baked to dryness, but it soon became apparent that the material was

unsuitable, and that the proportion of steam condensed on admission into the cylinder still exceeded that observable in large engines. He found also that any attempt to produce a better exhaustion by throwing in more injection water caused only a greater waste of steam. On reflection, he attributed some part of the difficulty to the boiling of water *in vacuo* at low heats, a discovery then recently made by Dr. Cullen, whereby the water in the cylinder would produce a steam, capable in part, of resisting the pressure of the atmosphere.

Watt was then led to experiment as to the temperature of water boiling under pressures greater than that of the atmosphere, from which it appeared 'that when the heats proceeded in an arithmetical, the elasticities proceeded in some geometrical ratio.'

Being now led to examine the bulk of steam which could be obtained from a given quantity of water boiling under atmospheric pressure, Watt made the following experiment:—'Into a Florence flask capable of holding $17\frac{1}{8}$ oz. of water, he poured 1 oz. of distilled water, and fitted a glass tube into the flask by a steam-tight joint made by packthread and putty.' He goes on to say:—'When the flask was set upright, the end of the tube reached nearly to the surface of the water, and in that position the whole was placed in a tin reflecting oven before a fire, until the water was wholly evaporated, which happened in about an hour, and might have been done sooner had I not wished the heat not much to exceed that of boiling water. As the air in the flask was heavier than the steam, the latter ascended to the top, and expelled the air through the tube. When the water was all evaporated, the oven and flask were removed and a blast of cold air was directed against one side of the flask to collect the condensed steam in one place.' Then he weighed the flask with these condensed globules in it, again heated the flask and dried it by blowing air into it with a bellows, and found the weight of the water to be rather more than 4 grains (estimated at $4\frac{1}{3}$ grains). Also the flask held $17\frac{1}{8}$ oz. of water, or 8,220 grains. From these numbers it was apparent that the volume of steam was about 1,900 times that of the boiling water from which it was generated.

Allowing for sources of error in the estimation, Watt appears to have considered that 1 cubic inch of water at 212° F. formed

1 cubic foot of steam at 212° F., and at the atmospheric pressure. Both estimates are too large, and Mr. Maxwell gives 1,650 as representing approximately the number of cubic inches of steam at 212° F. obtained from 1 cubic inch of water at its temperature of greatest density, viz., 39·1° F.

The next experiment was of great practical value:—A glass tube being bent at a right angle, one end was inserted horizontally into the spout of a tea-kettle and the other end was turned downwards into a vessel containing a known quantity of cold water taken from a well. The temperature of the water is not recorded.

Steam from the kettle was passed into the water until it began to boil, and the weight which it had then gained was found to be $\frac{1}{6}$ part of the original weight. Watt inferred that water when converted into steam can heat about 6 times its own weight of well-water to 212° F., or till it can condense no more steam, and he goes on to say: 'Being struck with this remarkable fact, and not understanding the reason for it, I mentioned the matter to my friend Dr. Black, who then first explained to me the doctrine of latent heat. On reflecting further, I perceived that, in order to make the best use of steam, it was necessary first that the cylinder should be maintained always as hot as the steam which entered it; and secondly, that when the steam was condensed, the water of which it was composed, and the injection itself, should be cooled down to 100° F., or lower, where that was possible. The means of accomplishing these points did not immediately present themselves; but early in 1765 it occurred to me that if a communication were opened between a cylinder containing steam and another vessel which was exhausted of air and other fluids, the steam, as an elastic fluid, would immediately rush into the empty vessel, and continue so to do until it had established an equilibrium; and that if that vessel were kept very cool by an injection or otherwise, more steam would continue to enter until the whole was condensed.' Then Watt proposed to employ a pump to extract both the air and the water from this second vessel, which formed the *separate condenser* of the improved steam-engine.

Other improvements 'followed as corollaries in quick succes-

ion.' Thus water packing was inadmissible, for if any water entered into a partially exhausted and hot cylinder, it would boil and prevent the production of a vacuum. This defect he proposed to remedy by employing wax, tallow, or other grease to lubricate and keep the piston tight. Then he saw that the open mouth of the cylinder would admit air and cool the interior thereof, and he therefore proposed to 'put an air-tight cover upon the cylinder with a hole and stuffing box for the piston to slide through, and to admit steam above the piston to act upon it instead of the atmosphere.' There still remained the cooling of the cylinder by the external air, and this he remedied by the use of an external cylinder containing steam (now called a *steam-jacket*) surrounded by another of wood, or of some other non-conducting substance.

WATT'S PATENT OF 1769

10. Having thus pursued the train of thought developed in carrying out the invention of a separate condenser, it may be useful to turn to the specification of the patent granted on January 5 1769 to James Watt (No. 913) for 'a new invented method of lessening the consumption of steam and fuel in fire-engines.' The document commences with an unfortunate sentence, viz. :—

'My method of lessening the consumption of steam, and consequently fuel, in fire engines consists in the following *principles*.'

Now it is a maxim of the law that there cannot be a patent for a principle, and accordingly the property in an invention which revolutionised the mechanical industry of the whole world was nearly shipwrecked on the technical objection that the method claimed was a principle and not a manufacture; and it was only after a long struggle that the question was determined in favour of the inventor. The Court of Common Pleas was unable to arrive at any decision, but the objection was finally disposed of by the strong common sense of Lord Kenyon, C.J., who observed :—'I have no doubt in saying that this is a patent for a manufacture, which I understand to be something made by the hands of man.' An account of the proceedings in Boulton and Watt *v.* Bull, and in Hornblower *v.* Boulton, is given in an 'Abstract of Patent Cases,' by the author of the present treatise.

The specification goes on to describe the invention of the separate condenser, and shows the sense in which the word *principle* has been employed, as follows :—

'*First.* That vessel in which the powers of steam are to be employed to work the engine, which is called the cylinder in common fire-engines, and which I call the steam vessel, must, during the whole time the engine is at work, be kept as hot as the steam which enters it.

'1. By enclosing it in a case of wood or other materials they transmit heat slowly.

'2. By surrounding it with steam or other heated bodies.

'3. By suffering neither water nor any other substance colder than steam to enter or touch it during that time.

'*Secondly.* In those engines that are to be worked wholly or partially by condensation of steam, the steam is to be condensed in vessels distinct from the cylinders, though occasionally communicating with them. These vessels I call *condensers*, and whilst the engines are working they ought to be kept as cool as the air in the neighbourhood by the application of water or other cold bodies.

'*Thirdly.* Whatever air or other elastic vapour is not condensed by the cold of the condenser is to be drawn out of the steam vessels or condensers by means of pumps wrought by the engines themselves or otherwise.'

The remainder of the specification is not important for the present purpose except towards the end, where the patentee states : —'Instead of using water to render the piston or other parts of the engines air and steam tight, I employ oils, wax, resinous bodies, fat of animals, quicksilver or other metals in their fluid state.'

There was no drawing annexed to the specification, and in this respect the description was imperfect.

11. It appears that in Watt's first experimental model the condenser consisted of two small pipes of thin tin-plate, each about 12 inches long, connected at their upper ends with the steam cylinder and at their lower ends with a common suction pump ; the tubes and pump being wholly immersed in a vessel of cold water. This would now be called *surface condensation.*

It further appears that the pipe condenser was afterwards

changed for an empty vessel, generally of a cylindrical shape, into which an injection of cold water played in the form of a jet, and the air-pump was enlarged in consequence of there being more water and air to extract. This is a *jet condenser.*

Watt says that 'the change was made because, in order to procure a surface sufficiently extensive to condense the steam of a large engine, the pipe condenser would require to be very voluminous, and because the bad water with which engines are frequently supplied would crust over the thin plates and prevent their conveying the heat sufficiently quickly.'

Portions of some such apparatus as that here referred to are to be found among the collection of Watt's models now preserved at South Kensington.

12. The annexed drawing approaches closely to the form of one of the early pumping engines with a separate condenser, and it is introduced in order to show that a steam-jacket was an essential portion of the steam cylinder. Here, as in Newcomen's engine, the piston and pump rods were suspended by chains from the working beam, and the work done by the steam was that of lifting a weight. When the engine was at rest the piston remained at the top of the cylinder.

The drawing shows a steam pipe S opening into a jacket or steam casing which surrounds the cylinder A, and which provides that a supply of steam shall always press down upon the upper surface of the piston P. The cylinder is now completely closed in, and accordingly the piston rod passes through a steam-tight box and packing at K, the construction of which will be explained in Chapter V., to which we refer for all such details. At the bottom of the cylinder is an eduction pipe leading into the condenser C, and there are two valves, E and D, the valve E opening into the eduction passage from the steam casing and the valve D being in the pipe itself. There is also an injection orifice for admitting cold water into the condenser, a foot valve R for preventing the return of any water or air after it has been drawn out therefrom, and an air-pump Q for removing from the condenser the water and air which are continually accumulating. At the top of the air-pump chamber there is a valve N (called a delivery valve), which opens into a reservoir or hot well, intended to receive the water that

has been warmed by condensation of the steam, and from which the supply for the boiler is continually being drawn. There is also a blow-off valve L, or valve opening outwards from the condenser, which corresponds to the snifting valve in Newcomen's engine.

In setting the engine in motion the first thing to be done is to clear all the air from the lower part of the steam cylinder and condenser, which is effected by allowing the steam to pass freely through

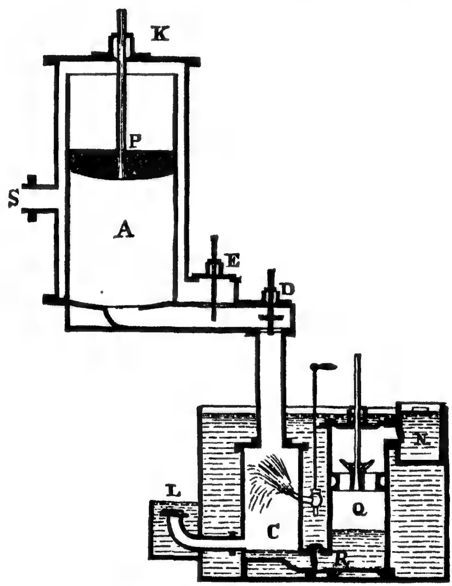


FIG. 4.

the condenser and to escape at the blow-off valve. The air being expelled, the engine can begin to move. The equilibrium valve E is closed, the eduction valve D remains open, and the injection cock is opened; a jet of cold water now rushes into the condenser and creates a partial vacuum, the steam from below the piston flows into the condenser and is converted into water, whereupon the pressure of the boiler steam on the upper surface of the piston carries it down and raises the pump rods. When the piston reaches the

bottom of the cylinder the eduction valve is closed as well as the injection orifice, and the equilibrium valve is opened, thereby permitting the steam from the boiler to flow freely into the space below the piston. This equalises the pressure on both surfaces, and the weight of the counterpoise or of the pump rods carries the piston again to the top of the cylinder just as in the case of Newcomen's engine. All this time the air-pump is at work, removing water or air from the condenser, and sending it through the delivery valve into the hot well.

The principle being that nothing colder than steam shall enter the cylinder during the working of the engine, the air which pressed down the piston in the atmospheric engine is replaced by steam at a pressure equal to or a little above that of the atmosphere. The function of the equilibrium valve is to allow steam to pass underneath the piston, and the condensation takes place in a separate vessel, The early commentators on Watt's engine (Dr. Robison, for example), speak with interest of the fact that 'the cylinder may be allowed to remain hot; nay, boiling hot, and yet the condensation may be completely performed.' The reason that this happens will be better understood when the properties of a vapour are discussed, but the instantaneous fall of pressure in the steam can hardly be accounted for without reference to the modern theory of the constitution of gases.

13. In the form above described, the engine should be regarded as a Newcomen's engine with steam instead of air acting upon the piston, and provided with a separate condenser. But a material change was soon introduced, for it was seen that many advantages would arise from cutting off the free communication between the boiler and the top of the piston by means of a third valve capable of regulating both the periods of admission and cut off of the steam in the upper part of the cylinder. At the present time three valves, viz. a *steam* valve, an *equilibrium* valve, and an *eduction* valve, are always to be found in a single-acting pumping engine of Watt's construction, and as a matter of precaution a fourth valve, or steam regulator, is interposed just on the boiler side of the steam valve, being kept permanently open while the engine is at work.

The drawing shows the arrangement of the three principal

valves in a single-acting engine of the early construction ; S is the steam valve which admits steam from the boiler, E the equilibrium valve, D the eduction valve which opens or closes the passage to the condenser.

The action is the following :—As before, the piston being at the top of the cylinder, and the air being blown out of the cylinder, condenser, and steam passages, the valves S and D are opened, and E is closed. At the same time a jet of cold water is admitted into the condenser, whereby the steam which has displaced the air in the interior of the engine is condensed and a partial vacuum is formed below the piston, the result being that the steam above the piston forces it down and raises the pump rods. When the piston reaches the bottom of the cylinder S and D are closed and E is opened, whereupon the steam which drove the piston down circulates freely on both sides of it, neither assisting nor retarding its motion, and the weight of the pump rods or counterpoise drags the piston to the top of the cylinder. The double movement is thus completed, and it will be seen that S is an independent valve which can be closed at any period of the stroke.

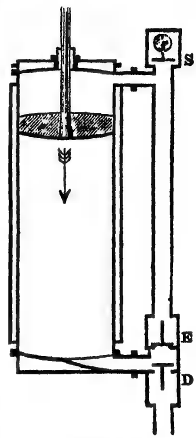


FIG. 5.

It should be noted that the method of representing the valves is conventional, the object being to indicate their operation, but not their construction.

GENERAL ARRANGEMENT OF THE WORKING PARTS IN WATT'S SINGLE-ACTING PUMPING ENGINE.

14. The drawing on p. 28 is inserted in order that the general arrangement of the engine may be placed before the student. It is taken from one of the series of lecture diagrams published by Messrs. Chapman and Hall in connection with the Science and Art Department, and gives a fair idea of the respective working parts. The beam is the first thing to notice as an example

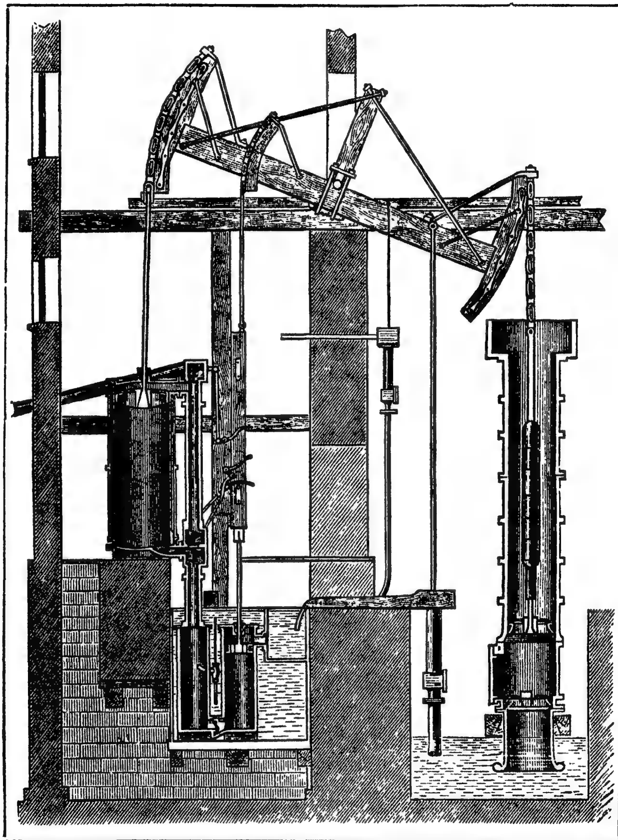


FIG. 6.—WATT'S SINGLE-ACTING PUMPING ENGINE.

of construction, for it is put together with a due regard to mechanical principles, and presents a striking contrast to the beam which appears in early drawings of Newcomen's engine.

The beam of a modern pumping engine is, of course, no longer a trussed wooden beam, but it is made either of cast or wrought iron. By way of comparison we may refer to an example to be found in a pumping engine at the Clay Cross Colliery, which has a cylinder 84 inches in diameter, with a stroke of 10 feet, and raises water from a depth of 420 feet. Here the beam is of wrought iron, formed by two massive slabs placed side by side, each 2 inches thick, and 7 feet 1 inch deep at the middle, but tapering to 3 feet 4 inches at each end. The full length of the beam is 36½ feet, and when the several parts are all put together, with a strong cast-iron centre piece for supporting the gudgeons, it weighs about 33 tons.

In our drawing the pump terminates suddenly in a cistern of water, but the intention is not to follow out what is done literally, and the pumps at Clay Cross are combined lifting and forcing pumps, the water being lifted through 150 feet, and forced up the remaining 270 feet by a plunger.

The valves in Watt's engine are worked by toothed sectors engaging with racks, a method which is represented in a drawing given in Chapter V. The operation of the valves is the same now as formerly, their construction being the only thing that has been varied; and at Clay Cross the steam valve is 14 inches in diameter, while the equilibrium and eduction valves are respectively 12 and 18 inches in diameter. Except in matters of detail there is no essential difference between an early example of Watt's single-acting engine and the Cornish pumping engine of the present day.

THE EXPANSION OF STEAM. WATT'S PATENT OF 1782.

15. Referring back to Article 13, where it is stated that S is an independent valve which can be closed at any period of the stroke of the piston, we have now to consider the consequences of closing the valve S when some portion only, say ½ or ¼ of the stroke, has been completed. Under such circumstances the engine is said to work *expansively*.

There was no such thing as the expansion of steam, either in Newcomen's engine or in Watt's earliest engine with a steam-

jacket fully open to the cylinder. In the atmospheric engine the function of the steam was merely to oppose a force which should continuously balance the pressure of the external air, and the work was done while the steam was being exhausted and not while it was in action. In the engine with a separate condenser the case was different, for the steam did the work and everything was ready for expansion as soon as provision was made for it by the introduction of a separate valve. But without a cut-off valve there would of course be no expansive working.

It appears that as early as 1776 Watt made experiments on the expansion of steam, and about that time he altered an engine at the Soho Works so as to test the result of an early cut-off. Other trials succeeded, but it was not until the year 1782 that Watt took out his patent for 'certain new improvements upon steam or fire-engines for raising water, and other mechanical purposes,' and gave a demonstration of the economy due to expansion.

The specification (No. 1,321) stated:—

'My first new improvement in steam or fire-engines consists in admitting steam into the cylinders or steam vessels of the engine only during some part or portion of the descent or ascent of the piston of the said cylinder, and using the elastic forces wherewith the said steam expands itself in proceeding to occupy larger spaces as the acting powers on the piston through the other parts or portions of the length of the stroke of the said piston.'

In other words, the steam-valve remains open until some definite portion of the stroke of the piston has been completed, and is closed during the remainder of the stroke.

In order to comprehend the effect produced we must refer to a law discovered by Robert Boyle in 1662, and subsequently verified by Marriotte. It is known as Boyle's or Marriotte's law, and is often termed the *first* law of the expansion of gases.

BOYLE'S LAW.

16. The law may be stated as follows:—The pressure of a portion of gas at a constant temperature varies inversely as the space it occupies.

In order to verify this statement roughly by experiment we

refer to a simple apparatus consisting of two pieces of strong glass tube A B, C D, each about $\frac{1}{4}$ inch internal diameter, and having their ends secured in a small metal box, F, provided with a stopcock. The tube AB is open at the top, and is a little more than 35 inches in length, while the shorter leg is somewhat over 10 inches long, and is provided with a cap closed by a screw-plug. A board having a scale graduated to inches carries the tubes, the zero of the scale being a little above the box, and the graduation for 10 inches marking the bottom of the plug, so that the space from 0 to 10 is a definite measured length of the tube C D.

The plug at D being unscrewed so that air can enter, a little mercury is poured in at B, and the cock F serves to withdraw any excess and to bring the level of the mercury to the zero of the scale. Then D is closed and mercury is introduced slowly at B until the level in A B is 30 inches in excess of that in C D. Supposing the barometer to mark 30 inches at the time of the experiment, it will now be found that the level of the mercury in C D is 5 inches. That is, the air in C D is compressed into half its volume by a pressure of two atmospheres. In this way the law may be approximately verified; and the important thing to be noticed is that it does not hold unless the temperature of the enclosed air remains unchanged. This is an imperative condition.

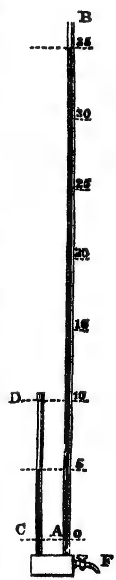


FIG. 7.

Note.—Since the pressure of a portion of gas at a constant temperature varies inversely as its volume, and since the density of the same portion also varies inversely as its volume, it follows that the pressure of a portion of gas varies directly as its density.

It is stated by Mr. Maxwell that this law 'is not perfectly fulfilled by any actual gas. It is very nearly fulfilled by those gases which we are not able to condense into liquids;' and moreover, that when a gas is about to pass by condensation into a liquid form 'the density increases more rapidly than the pressure.'

In the year 1829 MM. Dulong and Arago carried the experiment above described to an extreme degree, for the tube A B was

elongated until the pressure of the compressed air reached 27 atmospheres. These experimenters failed to detect any deviation from the law laid down by Boyle and Marriotte.

BOYLE'S LAW REPRESENTED BY A CURVE.

17. The application of Boyle's law to the expansive working of steam will be made more clear if we deal with a substance, such as air, having the same elastic properties, but which does not pass into liquid in the same manner.

Suppose the case of a cylinder with a circular base, partly filled with compressed air, and having a piston capable of moving along it without friction.

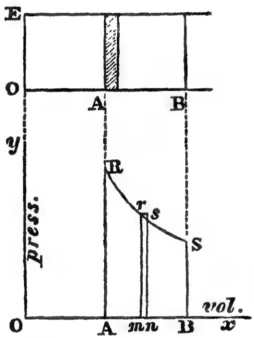


FIG. 8.

Take O x, O y at right angles to each other, and let O x represent a line along which volumes are measured, called a *line of volumes*, and O y a line along which pressures are measured, or a *line of pressures*. Starting with a volume of air enclosed in the space E A, it is evident that the travel of the piston represents the increase of volume of the enclosed air. Also, if A R be the pressure of the air in E A, the line B S will represent the pressure in E B, under the condition that

$$\frac{\text{B S}}{\text{A R}} = \frac{\text{vol. E A}}{\text{vol. E B}} = \frac{\text{O A}}{\text{O B}}$$

If a sufficient number of lines corresponding to B S be drawn the curve R S may be set out, and will present to the eye a series of changes of pressure and volume made in accordance with Boyle's law. But since the pressure of the enclosed air varies inversely as its volume, it follows that the product of the numbers representing its volume and pressure is a constant quantity.

That is, if O A $= v$, A R $= p$, we have the equation

$$p\,v = \text{a constant},$$

as an analytical representation of Boyle's law. It is known that

the equation O A × A R = a constant, represents that particular curve called an hyperbola, which may be a section of a right cone made by a plane parallel to its axis, the cone being of such dimensions that its asymptotes are at right angles to each other. Hence the curve R S is an hyperbola. In Chapter IV. the mode of representing a curve by an equation is explained.

The fundamental property of the curve of expansion, according to Boyle's law, is, as we have stated, that the temperature remains constant, and accordingly a name has been adopted for the curve which recalls at once to the mind this fact of uniformity of temperature. It is common to speak of it as an *isothermal* curve. The term is derived from two Greek words, and signifies a curve of equal temperature.

DIAGRAM OF WORK DONE DURING EXPANSION.

18. The geometrical method of treating the subject of the expansion of a gas possesses another advantage, viz., that the work done by the enclosed air in forcing the piston from A to B is represented by the area A R S B.

Conceive that the air in the cylinder expands from a volume O A and pressure A R to another volume O B and pressure B S, and let it be required to represent the work done during this expansion by a diagram, the temperature of the air being supposed not to change during the expansion. (Hereafter we shall see that this will not happen unless heat is supplied artificially.) Take r, s, two points in the curve R S very near to each other, and draw $r\,m$, $s\,n$ perpendicular to O x, and suppose that the pressure of the air does not change sensibly during its expansion from volume C m to volume O n.

Since the space moved through by the piston is directly proportional to the increase of volume, it follows that the rectangle $s\,m$, which is the product of the pressure $r\,m$ and the volume $m\,n$, is also the product of the pressure $r\,m$ and the space described by the piston in traversing $m\,n$; that is, the rectangle $s\,m$ represents work done by the air upon the piston in moving it through the space $m\,n$. And the same is true for each small element of the motion. But the limit of the sum of all such rectangles is the whole

area A R S B; therefore A R S B represents the work done by the air upon the piston in expanding from volume O A to volume O B.

THE DIAGRAM OF WORK DONE DURING EXPANSION. WATT'S PATENT OF 1782 (*continued*).

19. The description of the invention of expansive working will now be readily understood. The drawing is copied from the specification of the patent, and presents the *first published example* of the *diagram of energy* as applied to a steam-engine.

The cylinder is described as being perfectly closed in at the upper and lower ends, the piston P being accurately fitted to the cylinder so that it can easily slide up and down without suffering any steam to pass. The piston rod passes through an opening in the cover, which is made air and steam tight by a collar of oakum well greased, and contained in the box O. Near the top of the cylinder there is a pipe E to admit steam from a boiler. The whole cylinder is enclosed in a case M, M, containing steam, and there are also cases N, N, containing steam at the two ends thereof.

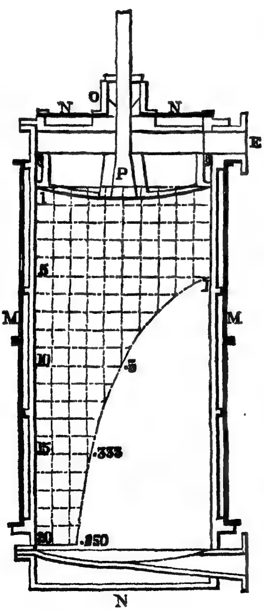


FIG. 9.

The available length of the cylinder being subdivided into twenty equal parts, numbered 1, 2 . . . 20, steam at the atmospheric pressure (say 14 lbs. on the square inch) is admitted freely, while the piston travels over five divisions, and is then shut off. Hence, at division 10 the pressure will have fallen to $\frac{1}{2} \times 14$ lbs. or 7 lbs. At division 15 it will be $\frac{1}{3} \times 14$ lbs., or $4\frac{2}{3}$ lbs., and at division 20 it will be $\frac{1}{4} \times 14$ lbs. or $3\frac{1}{2}$ lbs.

Watt here assumes that Boyle's law applies strictly to the

expansion of steam. Further, the vertical divisions represent the travel of the piston, and the horizontal lines represent the pressure of the steam. The subdivisions of the steam pressure are noted on the diagram exactly as Watt estimated them, but are omitted here for want of space. They are :—

1, 1, 1, 1, 1, ·83, ·711, ·625, ·555, ·500, ·454, ·417, ·385, ·357, ·333, ·312, ·294, ·277, ·262, ·250.

Then each of these numbers representing the steam pressures at the respective points 1, 2, 3 . . . 20, is supposed to remain constant during the passage from one division to the next in order, and is multiplied into the number 1 representing the space travelled over by the piston, and in that way a series of rectangles are obtained, each of which is an area representing work done. The addition of all the rectangles would give an area a very little less than that of the true diagram of work, that is, of the diagram set out, one side of which is the curved line in the sketch.

The sum of all the 20 numbers enumerated is 11·562, which, divided by 20, gives ·578, or approximately ·57, as the mean pressure of the steam during the stroke.

But $\frac{57}{100}$ is greater than $\frac{1}{2}$, and the conclusion follows in these words:—'Whereby it appears that only $\frac{1}{4}$ of the steam necessary to fill the whole cylinder is employed, and that the effect produced is equal to more than $\frac{1}{2}$ of the effect which would have been produced by one whole cylinder full of steam, if it had been permitted to enter freely above the piston during the whole length of its descent.'

By this explanation Watt showed conclusively that the direct result of expansive working was to obtain an increased amount of work by the consumption of a given quantity of steam.

But the principle cannot be carried to any extreme degree, for the increase in the size of the cylinder, and the inequality in the pressure on the piston would soon present formidable difficulties. It will be necessary to recur to this subject after some preliminary enquiry into the principle of heat engines. Not only is expansive working a source of direct economy, but it is valuable also as a regulator, that is to say, it enables an engine to put forth variable amounts of power without the necessity of a permanent alteration in the pressure of the boiler steam.

It is important to observe that in the drawing of the specification the cylinder has a steam-jacket surrounding its ends as well as its sides. The proposition in the original patent was that the cylinder should be kept as hot as the steam which entered it, and Watt was too good an engineer to enter upon a discussion as to the behaviour of steam when admitted into the cylinder at a total pressure of 14 lbs. per square inch, and at the same time to show the cylinder entirely unprotected from the cold of surrounding bodies. The true value of the steam-jacket will be understood after the next two chapters have been examined, but it may be permitted to say that it is unfortunate that the teaching of the great master should have been so soon disregarded by those who came after him—for example, Tredgold, in his large work on the steam-engine, enters into an elaborate attack upon the steam-jacket, which he sums up as follows:—'I hope this will be sufficient to establish the truth, that the steam-case is a useless addition to the expense of an engine.' This was before practical men had taken account of the conversion of heat into work.

THE DOUBLE-ACTING ENGINE. WATT'S PATENT OF 1782 (*continued*).

20. In order to adapt the steam-engine for driving machinery much yet remains to be done. Something must be known of the first principles of the conversion of motion before the problem can be fully grasped, and at present it may suffice to refer to a double-acting engine as set forth in the patent (No. 1321).

Watt says:—'My second improvement upon steam or fire-engines consists in employing the elastic power of the steam to force the piston upwards, and also to press it downwards alternately, by making a vacuum above or below the piston respectively, and at the same time employing the steam to act upon the piston in that end, or exerted upon the piston only in one direction, whether upwards or downwards.'

The object here is to allow the steam to enter on one side of the piston, while the other side is in free communication with the condenser. For this purpose there are four valve chests, viz. at A, C, B, and F. In each chest there is a valve opening upwards, and between the valves A and C there is a passage leading to the

top of the cylinder, while between B and F there is a passage leading to the bottom of the cylinder. The steam-pipe K A D B

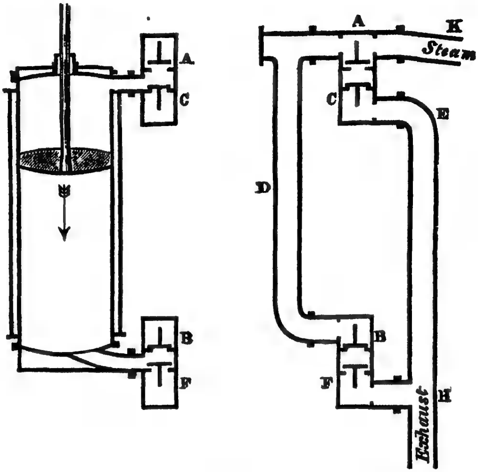


FIG. 10.

enables steam to enter either the top or bottom of the cylinder, according as the valve A or the valve B is lifted from its seat. In like manner by opening the valve C, the top of the cylinder is freely open to the condenser by means of the pipe C E F H; and by opening F the bottom of the cylinder also opens to the exhaust. Thus, in the working of the engine A is opened for steam and F for exhaust, whereupon the piston descends; otherwise B is opened for steam and C for exhaust, and the piston rises.

HORNBLOWER'S PATENT OF 1781.

21. There can be no question as to the fact that Watt invented the expansive working of steam, but, technically, he does not stand first in the records of the Patent Office, for he was anticipated by a patent of Hornblower for a single-acting pumping engine which dates from the year 1781.

The specification of this patent (No. 1,298) is a mere statement of what is to be done, and rather publishes an idea than an invention. The patentee says:—

'1. I use two vessels, in which the steam is to act, and which in other steam-engines are generally called cylinders.

'2. I employ the steam after it has acted in the first vessel, to operate a second time in the other, by permitting it to expand itself, which I do by connecting the vessels together, and forming proper channels and apertures, whereby the steam shall occasionally go in and out of the said vessels.

'3. I condense the steam by causing it to pass in contact with metalline surfaces while water is applied to the opposite side.'

We can obtain no further information from the specification,

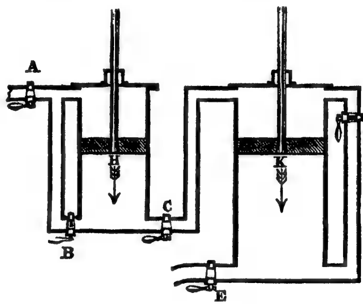


FIG. 11.

and the mode of carrying out the improvement is therefore taken from other sources, the sketch given being a mere lecture diagram.

The engine is single-acting, and works with a separate condenser, after the method invented by Watt. The valves A, C, and E are open while B and D are closed, whereby steam from the boiler is entering the small cylinder H, and is also escaping from below the piston into the larger cylinder K, while steam from below K is passing into the condenser. The result is that both pistons descend together. When they arrive at the end of their respective strokes the valves A, C, and E are closed while the equilibrium valves B and D are opened, and the pressure of the steam is thus equalised on both surfaces of each piston, which is all that is required for performing the up stroke.

It will be noticed that the cylinders are of unequal length, the

reason being that the piston rods are attached to the same working beam, and that the small, or high-pressure cylinder, is nearer to the centre of motion of the beam.

WATT'S INVENTION OF THE INDICATOR.

22. In giving evidence before a parliamentary committee in 1829, Mr. Farey mentioned that Watt had been the first to invent and apply to steam-engines an instrument called an *indicator*, with the object of determining the amount of *plenum* and *vacuum* formed on either side of the piston of an engine during the work, and further that Watt himself had kept the invention in the complete and perfect form which was essential to its successful use a profound secret for many years. Mr. Farey also said :—'An instrument fell into my hands in Russia, where it had been made by some of the people sent out from England with Mr. Watt's steam-engines. On my return to England I made one, and also showed several other engineers how to make such for themselves, and since that time every one of those persons has very greatly improved his practice by the light it has enabled him to throw upon the operation of steam in an engine.'

In an appendix by Mr. Watt to Dr. Robison's 'Mechanical Philosophy,' it is stated that although a barometer serves very well for ascertaining the degree of exhaustion in the condenser of an engine, it is quite unsuited for testing the degree of pressure or exhaustion in the steam cylinder on account of the vibrations to which the mercury would be subjected by the rapid fluctuations which take place. Then Watt proceeds to describe his invention of an *indicator*, or instrument for observing the changes of pressure of the steam or vapour in the cylinder of an engine.

A cylinder, about 1 inch in diameter and 6 inches long, exceedingly truly bored, has a solid piston accurately fitted to it, so as to slide easily by the help of some oil; the stem of the piston being guided in the direction of the axis of the cylinder, so that it may not be subject to jam or cause friction in any part of its motion. The bottom of this cylinder has a cock and small pipe joined to it, which, having a conical end, may be inserted in a hole drilled in the cylinder of the engine near one of its ends, so that

by opening the cock a communication may be effected between the inside of the cylinder and the indicator. There is also a frame with a steel spring attached to it by one end, the other end being fastened to the piston. The cylinder is open to the atmosphere at the top, and the piston remains at rest when the steam pressure is equal to that of the atmosphere, but rises or falls as the pressure becomes greater or less than the air pressure. The amount of the rise or fall will be determined by the strength of the spring, which must be tested, and a graduated scale together with an index at the end of the piston serves for measuring pressures.

The account here set forth appears to be all that Watt made public, and it leaves the instrument in an unfinished state. If, however, the index at the end of the piston be replaced by a pencil, and a board carrying a sheet of paper be caused to move to and fro underneath the pencil with a motion identical with that of the piston of the engine but on a diminished scale, the direction of motion of the pencil being vertical and that of the board being horizontal, it will be found that the pencil traces upon the paper a closed curve, which is Watt's diagram of work.

The instrument is shown in the drawing, which is copied from a sketch of early date, and is not very correct in proportion. It is screwed into an opening made in the cylinder at one end, whereby the steam passes through the cock K into the lower end of the cylinder, and presses upwards against the piston P. The piston rod carries a pencil R which traces out the diagram on a board moving to and fro horizontally in the frame A B C D. When the pressure of the steam balances that of the external atmosphère the piston is at rest, the spring being in its normal position and exerting no force to resist either extension or compression. If, in this state of things, the sliding

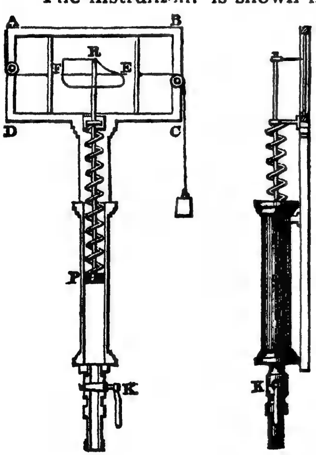


FIG. 12.

board be moved to and fro, the pencil will trace the horizontal line E F, technically called the ***atmospheric line.*** Whereas, if the pressure of the steam (or uncondensed vapour below the piston) be either greater or less than that of the atmosphere the pencil will rise or fall, and the curve (which is a rough copy of the diagram of work) will be the result of combining the motion of the pencil with the to and fro movement of the board. The string passing upwards round the pulley on A D is attached to some moving part of the mechanism in such a manner that the motion of the board shall reproduce that of the main piston, but reduced until the travel is limited to the breadth E F. A weight is fastened to a second string in order to produce the return movement of the board.

Hereafter it will be explained that the curve traced out by the indicator pencil gives more than a mere measure of the actual performance of the engine, and that it enables us to clear up many obscure points connected with the construction and action of the working parts.

THE PROPERTIES OF A VAPOUR.

23. It is difficult, in writing a book of this kind, to treat every subject in a perfectly logical order. Strictly speaking we ought to begin with a complete series of definitions and experiments, and suppose nothing to be known until it has been explained in due course. If this method were adopted the chapters might gain in methodical arrangement but they would be intolerably dull, and it seems preferable to assume a general acquaintance with things which every reader would know, and to enter upon a more complete examination at any particular stage where it would be useful.

Recurring to the properties of the vapour of water, we remark that water gives off vapour at all temperatures, whether in a liquid or frozen state, and that the vapour, being a gas, has that property of indefinite expansion which characterises gases. It follows that if a small quantity of vapour be formed in a closed vessel, however large, it will at once expand so as to fill the whole of it, and will exert a pressure against the enclosing surface.

There are two cases to be considered—

1. When the vapour is in contact with the generating liquid.

2. When it is entirely separated therefrom.

A simple experiment may be arranged for giving some insight into the behaviour of vapour when in contact with the generating liquid.

1. Take a barometer tube, say about 33 inches long, and closed at one end. Fill it with clean mercury, which may be done by pouring in mercury nearly to the level of the open end, closing the end with the finger and then passing the large bubble of air two or three times up and down the tube. This removes all the minute bubbles of air which adhere to the glass, and mercury may be added up to about $\frac{1}{2}$ an inch from the open end; then fill this empty space with bisulphide of carbon (a very volatile liquid), and invert the tube in a deep well of clean mercury, as shown in the diagram. The bisulphide of carbon will rise to the top of the tube, vapour will form in the empty space above the mercury, and will, by its pressure, drive down the column of mercury so as to shorten it considerably as compared with the column in an ordinary mercurial barometer. We have accordingly a small layer of liquid lying on the top of the mercury and several inches of apparently empty space above the liquid.

FIG. 13.

A singular result may now be exhibited. Depress the tube by the finger so as to sink it in the well, or cause it to rise higher, when it will be found that the height of the column A P remains absolutely constant. If the tube be raised quickly the liquid begins to boil, fresh vapour is formed instantly, and the pressure is kept at a constant intensity. On the other hand, a portion of the vapour passes into the liquid state when the space which it fills is contracted, and nothing will alter permanently the height of the mercurial column except a permanent change in the temperature of the liquid and of the tube.

Another experiment is instructive, as illustrating the action of vapour in the condenser of an engine. A glass receiver, H, from 4 to 5 inches in diameter, with a wide neck, has a cork fitted into it, through which three small tubes are passed. One tube, A B C,

is a bent barometer tube about 36 inches long and dipping into a vessel of mercury at C. Another is a tube, fitted with a stopcock, and terminating in a small glass cap, D. The third tube, E F, is connected with an air-pump.

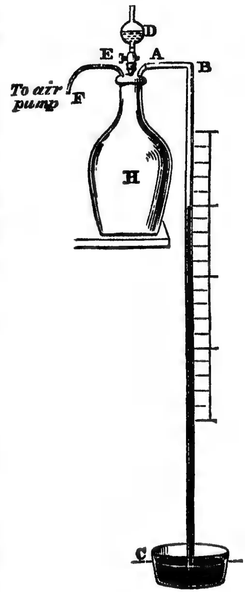


FIG. 14.

On pumping out air from the receiver we have an illustration of the barometer gauge of a condenser. The pressure of the air in H is diminished in the same proportion as that in which the mercury rises in B C, and by comparison with an ordinary barometer the exact degree of exhaustion can be estimated. Thus, if the top of the scale was marked 30 inches and the mercury stood at 25 inches, it would be said that the pressure of the air in H was competent to support 5 inches of mercury. In common parlance that is called a vacuum of 5 inches, a phrase not very correctly adopted. Pour now some ether into D, and open the stopcock just enough to allow the pressure of the external air to force a little of the liquid into the receiver. In an instant vapour is formed and the mercury drops through several inches. The vapour of ether may be then pumped out, and the mercury will rise as before, but it may be again as suddenly depressed by the admission of a fresh supply of ether.

The rapidity with which vapour forms in *vacuo* is strikingly shown by these experiments, the results of which are in strict accordance with the known laws which regulate the behaviour of a vapour when in contact with the generating liquid, viz.:—

1. Vapour exerts pressure.

2. Vapour forms with great rapidity in an empty space, though slowly in air.

3. The pressure of a vapour rises as you exalt its temperature

4. The further formation of vapour is arrested by the pressure of the vapour already formed.

5. If the temperature be given, reduction of volume causes liquefaction, leaving the pressure unaltered.

6. If the volume be given, reduction of temperature causes liquefaction.

24. When a vapour is formed in a closed space, and is in contact with the generating liquid, it is said to be *saturated.* That is the technical word for expressing its physical condition when just ready to yield some portion of liquid on the smallest increase of pressure or reduction of temperature. Thus steam at 212° F exerts a pressure equal to that of the atmosphere, and is called *saturated steam*, the condition being that it is taken direct from the boiler without being separated at a lower temperature and heated up to 212° F. by subsequent treatment.

If it were so heated it would approach the condition of a permanent gas, and would be called *superheated* steam. The two extreme cases are those of a saturated vapour and a so-called permanent gas. The experiment gives an example of the former; thus the vapour of bisulphide of carbon becomes in part liquefied rather than support an additional pressure of one or two inches of mercury. There is one gas which is ordinarily permanent, but may be liquefied by pressure without difficulty, viz., carbonic acid, and its properties have been investigated in a systematic manner by Dr. Andrews.

ISOTHERMAL LINE FOR A VAPOUR.

25. The behaviour of a vapour when near the point of saturation may be studied by the aid of a diagram. Conceive that a mass of vapour exists at a volume O N, and pressure R N, its temperature being above that at which condensation would begin. Conceive also that its temperature remains constant during any changes of volume and pressure through which it is about to pass. According to Boyle's law the expansion or contraction of the vapour, so long

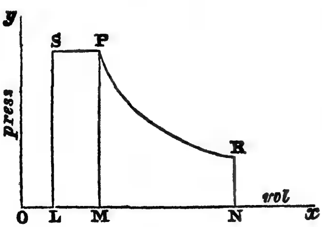


Fig. 15.

as it possesses the properties of a gas, will be given by the curved line P R. Suppose, further, that when the pressure is increased to P M liquefaction begins. At this point reduction of volume may go on, but the pressure cannot be increased, and the way to express that fact geometrically is to carry the line P S in a direction parallel to O x; the result being that the 'isothermal' is no longer curved throughout, but suddenly passes into a straight line at the point of saturation.

EXPERIMENTAL DETERMINATION OF VAPOUR PRESSURE.

26. Let us now examine the methods adopted for ascertaining the pressure of the vapour of water at different temperatures, both above and below 212° F.

The earliest accepted authority on this subject is Dalton, who published his results in the 'Memoirs' of the Lit. and Phil. Soc., Manchester, in 1802 (vol. v. page 551).

It appears, however, that Watt had obtained approximate results as to the vapour pressure of water while working out his discovery, and that his mode of experimenting was substantially that adopted by Dalton.

The paper in the Manchester 'Memoirs' begins with some prefatory observations on the remarkable increase observed in the elastic force of a vapour when heat is applied directly to the generating liquid:—

'By increasing the temperature of any gas a proportionate increase of elasticity ensues; but when the temperature of a liquid is increased the force of vapour from it is increased with amazing rapidity, the increments of elasticity forming a kind of geometrical progression to the arithmetical increments of heat. Thus the ratio of the elastic force of atmospheric air at 32° to that at 212° is nearly 5 to 7, but the ratio of the force of aqueous vapour proceeding from water of 32° and 212° is as 1 to 150 nearly.'

This striking fact being pointed out, Dalton goes on to describe his experiments, and states that he introduced a very little water into the inside of a barometer filled with mercury, leaving a layer of $\frac{1}{8}$ or $\frac{1}{10}$ inch of water upon the top of the mercurial column. The upper part of the tube was then enclosed in a larger glass tube, 2 inches in diameter and 14 inches long, by

means of two perforated corks which formed the top and bottom of a water chamber or hot bath enveloping the whole of the upper portion of the barometer tube, and wherein the water was maintained at a fixed temperature by means of a lamp. The vapour enclosed in the top of the barometer as well as the generating layer of liquid thus became heated at a constant temperature, and the depression of the column of mercury as compared with the column in a standard barometer showed the amount of pressure exerted by the saturated vapour.

In this way Dalton had 'water as high as 155° F.' surrounding the vapour tube. For higher temperatures up to 212° F. he modified the apparatus, and employed a tin tube 4 inches in diameter as a casing for the bath; also the observation was made with a siphon barometer having two parallel legs, whereof one was enclosed in the bath, and the reading of the mercury in the leg outside the tin tube gave the required depression of the column as due to the pressure of the vapour.

27. Dr. W. A. Miller gives the following table of the pressures of the vapours of several liquids estimated in inches of mercury. Thus it appears that at 50° F. the vapour of bisulphide of carbon will depress the mercurial column through 7·846 inches, a fact which is apparent when trying the experiment described in Art. 23.

Temperature F.	Ether	Bisulphide of carbon	Water	Alcohol	Oil of turpentine
— 4	2·725	—	·036	·131	—
14	4·356	3·110	·082	·256	—
32	7·146	5·008	·182	·501	·082
50	11·278	7·846	·361	·948	·090
68	17·117	11·740	·686	1·732	·168
104	35·971	24·310	2·168	5·159	·460
140	68·121	43·71	5·874	13·776	1·058
176	116·03	79·94	13·998	32·00	2·408
212	193·72	130·75	30·00	66·33	5·310

We have seen that the condenser of a steam-engine has for its object the complete discharge of all steam from the working cylinder after it has done its work in propelling the piston. The degree of completeness with which this is effected will depend entirely on the temperature of the water after condensation, and

the table of pressures of the vapour of water shows at a glance what may be done. If ice at 32° F. were converted by the waste steam into water at 32° F. the pressure of the vapour left in the cylinder would fall to $\frac{1}{5}$ inch of mercury. The temperature of the condensing water is, however, commonly 110° F., giving off vapour capable of supporting a pressure of $2\frac{1}{2}$ inches of mercury. If a smaller quantity of condensing water be used it will be raised to a proportionately higher temperature, and a less perfect condensation will be effected. At 212° F. the object of the condenser would be entirely frustrated.

THE TEMPERATURE OF HIGH PRESSURE STEAM RISES WITH ITS PRESSURE.

28. It is well known that when water is confined in a closed vessel and heated, the pressure of the vapour formed therein continually increases. The precise temperature of the vapour which corresponds with any assigned pressure has been a subject of careful enquiry, and an apparatus called a Marcet's boiler has been designed for exhibiting the relation to a class. It is in a form which forbids any exact determination, but the student may contrast it with the arrangement employed by Regnault, and described in Art. 29.

The apparatus consists of a small boiler, provided with a thermometer and a mercurial pressure gauge. The drawing shows the boiler containing a small quantity of mercury covered by a layer of water resting upon it. The mercury is intended for filling the pressure gauge, which is a piece of barometer tube, C D, open at both ends, and passing down nearly to the bottom of the boiler. E F is a thermometer about 20 inches in length, whose graduations begin at 130 and go on to 250. A large thermometer is chosen, in order that its graduations may be seen at a distance. H is a pipe provided with a stopcock.

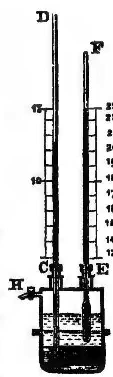


FIG. 16.

On applying heat to the boiler by a Bunsen burner or a spirit lamp the temperature soon rises above 212° F., and some mercury will ascend the tube, by reason that the pressure of the enclosed vapour becomes greater than that of the external air

The height of the column of mercury denotes the pressure of the vapour, and the corresponding temperature given by the thermometer may be observed; thus at 230° F. we should find the column at a height of about 12½ ins., and so on. The effect of opening the stopcock should be noticed; for, with a little care, it is easy to keep a small jet of steam blowing off without any fall in temperature or pressure, just as in the case of the boiler of a working engine, whereas, if the stopcock be fully and suddenly opened, the pressure and temperature drop at once, and the mercury in the thermometer very quickly falls to 212° F.

REGNAULT'S EXPERIMENTS FOR DETERMINING THE PRESSURE OF THE VAPOUR OF WATER.

29. The methods above described have been improved upon by Regnault, who has published a complete series of observations of the pressure of the vapour of water, ranging from −32° C. as far as 230° C.

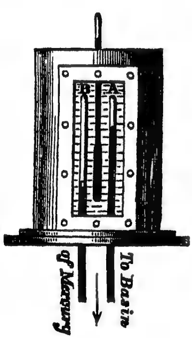


FIG. 17.

For temperatures below 0° C. a special apparatus is required, a description of which is beyond the scope of this book, while for temperatures ranging from 0° C. to 50° C. the apparatus shown in fig. 17, which closely resembles that of Dalton, has sufficed.

Two barometer tubes, corresponding to those of Dalton, stand side by side in the same vessel of mercury. The tube A is a common barometer, and the tube B is also a barometer, but with a small layer of water resting on the top of the mercury. The upper portions of both tubes are enclosed in a metal cylindrical vessel, filled with water, and provided with a glass window. The water in this vessel is heated by a lamp, and is agitated so as to keep the temperature uniform throughout, while the depression of the mercury in B is noted by comparison with the column in A, the difference in altitude of the two columns giving the amount of vapour pressure at the temperature of the observation.

For temperatures above 50° C. an apparatus has been con-

trived involving a special principle. The idea carried out has been to subject the water to the pressure of an artificial atmosphere capable of being regulated and measured with extreme nicety. The mercurial gauge no longer dips into the boiler, but a separate receiver connected with a pump is employed for producing an artificial pressure on the surface of the heated water.

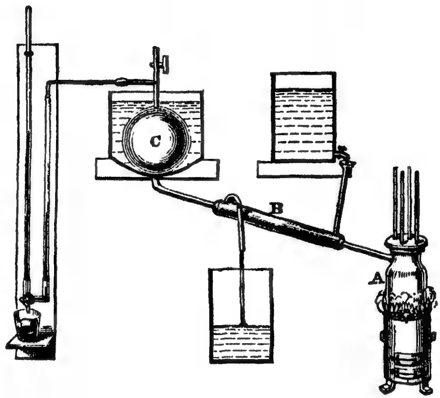


FIG. 18.

1. There is a boiler, A, placed over a furnace, and fitted with four thermometers for ascertaining the temperature.

2. A condensing tube, B, is inclined upwards at an angle, and is surrounded by an envelope of cold water. Any steam issuing from the boiler would condense in this tube and drain back again.

3. A globular reservoir of air, C, is enclosed in a vessel of cold water, and is maintained at a constant pressure, either greater or less than that of the external air, by means of a compressing or exhausting pump. This reservoir has a free passage through B into the boiler, and forms the atmosphere under the pressure of which the vapour is generated.

4. A measuring instrument of special construction is used for determining the pressure of the air in C, and is capable of being read to a pressure of twenty-seven atmospheres. In the drawing a mercurial siphon gauge serves to exhibit the nature of the measure-

ment, which is the same in principle to whatever extent it may be carried.

By this apparatus Regnault was enabled to measure accurately the temperature of the vapour, and at the same time to preserve a nearly constant artificial pressure upon the surface of the water in the boiler.

Note.—Hitherto the term 'pressure' has been used in its ordinary sense, but the word has a technical meaning, and is used to denote the *pressure in pounds on a square inch of surface.* When we say that the pressure of steam in a boiler is thirty pounds, we mean that the pressure of the enclosed gas on each square inch of the surface of the shell is thirty pounds.

We append a few results of the pressures of the vapour of water estimated in inches of mercury at the sea level at different temperatures on Fahrenheit's scale, the place of observation being in latitude 53° 21′. Our authority is Mr. Balfour Stewart, and the numbers are, no doubt, of a high degree of accuracy:—

Temperature Fahrenheit	Pressure in inches of mercury	Temperature Fahrenheit	Pressure in inches of mercury
32	·1810	215	31·73
40	·2475	220	34·98
50	·3607	225	38·50
60	·5178	230	42·30
70	·7327	240	50·85
80	1·0227	250	60·76
100	1·917	270	85·30
120	3·423	300	136·72
150	7·540	350	274·78
200	23·435	400	503·90
212	29·898	430	698·58

CHAPTER II.

HEAT IS NOT A MATERIAL SUBSTANCE.

30. We pass on to describe two principal attacks made upon the theory that heat is a material substance, and shall give some details of Joule's experiment for determining the numerical measure of work done by the expenditure of heat.

The sketch will be very brief, inasmuch as the subject matter is only introductory to the purpose of this volume.

It is worthy of notice that the conception that heat was in some way caused by motion had been entertained before the time of Black, as to which it is customary to quote the following passage from Locke's writings, where it is stated :—'Heat is a very brisk agitation of the insensible parts of the object, which produces in us that sensation from whence we denominate the object hot; so what in our sensation is heat, in the object is nothing but motion.' This idea did not find favour with Black, who argued against the possibility of accounting for the phenomena of latent heat on any such hypothesis ('Lectures,' p. 125), in the following terms: 'Some persons may perhaps imagine that the heat which thus disappears does not truly enter into the melting ice or become combined with that into which it is changed. This heat is perhaps entirely extinguished and destroyed. As heat has been supposed by some to consist in a rapid tremor or motion of the particles of bodies, or of some subtle matter that is intermixed with them, those who choose to adopt this opinion may imagine that motion may meet with friction and resistance in the ice, and that a part of it may be thus destroyed or the moving parts brought to rest.' Then he combats the idea thus set up by showing experimentally that 'while water is congealing it is constantly imparting heat to the air without becoming cooler itself,' and he considers that this heat must

have been previously absorbed or concealed in the water on the last occasion of its becoming liquefied by the melting of ice.

The mistake here made consisted in adopting a belief that the motion of heat could be destroyed. At the time of Newton it was supposed that the motion arrested by fricton was absolutely lost and put out of existence. Any such idea is now entirely abandoned, and Black's reasoning has no application.

By way of contrast to the erroneous statement thus laid down, it may be useful to lead up concisely to the modern views entertained as to the nature of heat.

COUNT RUMFORD'S EXPERIMENT ON THE PRODUCTION OF HEAT BY FRICTION.

31. A first overwhelming blow to the doctrine of caloric was given by Count Rumford's experiment of causing water to boil by the agency of mechanical force, and the following details are extracted from a paper read before the Royal Society in 1798.

In casting guns it is usual to leave a cylindrical head of metal at the muzzle end so as to ensure soundness of structure, the mould being placed in a vertical position with the muzzle end upwards.

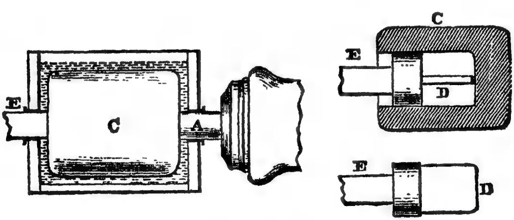


FIG. 19.

The drawing shows the end of a six-pounder brass gun, having a cylindrical neck of solid metal, A, 2·2 inches in diameter, and 3·8 inches in length. Beyond the neck the waste portion of metal forming the head for the casting was shaped into a cylinder C, 7·15 inches in diameter and 9·8 inches in length, having a cylindrical cavity bored out for the reception of a hard steel blunt borer. The borer was made from a plate of steel 3·5 inches wide

and ·63 inch thick; it is marked D in the figures, being shown both when turned edgeways and also when presenting its flat side. The cavity of the cylinder is given in section, with the borer *in situ*, the piece marked E being a rectangular iron bar terminated in a cylindrical plug and holding the borer D.

The borer was firmly held at rest and was pressed against the base of the cavity by means of a screw, the estimated pressure being 10,000 lbs. The gun itself was rotated by horses, the number of revolutions being 32 per minute.

The cylinder was enclosed within a deal box shown in section in the diagram. The box was 11·5 inches long, 9·4 inches wide, 9·6 inches deep, and it contained 18·77 lbs. of water. The square bar E, and the cylindrical stem A passed through packed water-tight openings in the sides of the box. The temperature of the water at the commencement of the experiment was 60° F.

The rotation of the gun under a pressure of 10,000 lbs. caused a considerable evolution of heat, traceable to the friction of the rubbing surfaces, and the heat so generated was but slowly conducted away by the comparatively slender neck of the cylinder. The result was that the temperature of the water rose as the trial went on, and at the end of one hour a thermometer placed in the water marked 107° F. At the end of the next half-hour the temperature had risen to 142° F., then in another half-hour to 178° F., and, finally, at the end of two and a half hours, the water boiled. In describing this result, Rumford breaks out into an enthusiastic recital of the effect upon those who witnessed it, and exclaims: 'It would be difficult to describe the surprise and astonishment expressed in the countenances of the bystanders on seeing so large a quantity of water heated and actually made to boil without any fire.' He goes on to say:—

'By meditating on the results of these experiments, we are naturally brought to that great question which has so often been the subject of speculation, namely, What is heat? Is there any such thing as an *igneous fluid*? Is there anything that, with propriety, can be called caloric?'

The conclusion which he draws is full of sound philosophy, and is a statement which the student should examine carefully and carry in his mind through the enquiries here presented:—

'In reasoning on this subject we must not forget to consider that the source of heat generated by friction in these experiments appeared evidently to be inexhaustible.

'It is hardly necessary to add that anything which an insulated body or system of bodies can continue to furnish without limitation cannot possibly be a material substance; and it appears to me to be extremely difficult, if not impossible, to form any distinct idea of anything capable of being excited and communicated in the manner heat was excited and communicated in these experiments except it be motion.'

DAVY'S EXPERIMENT ON THE MELTING OF ICE BY FRICTION.

32. On the recommendation of Count Rumford, Davy was appointed to a lecturership at the Royal Institution in 1802. His experiment in refutation of the doctrine of caloric is regarded as conclusive.

In an atmosphere at a temperature of 29° F. he rubbed together two small slabs of ice, each 6 inches long, 2 inches wide, and $\frac{3}{8}$ inch thick. The slabs were attached by wires to iron bars, and the friction was continued for several minutes.

The result was that the ice melted at the surfaces of contact, producing water at a temperature of 35° F.

Now a mass of water is known to contain an absolute quantity of heat far greater than that contained in an equal mass of ice, and it is therefore impossible to account for the presence of this heat on the assumption that heat is a material substance.

Davy's conclusion is a wonderful example of clear insight into the nature of heat, and we shall adopt it as the guiding statement in considering the working of heat engines. It is expressed in the following sentence:—

'The immediate cause of the phenomenon of heat is motion, and the laws of its communication are precisely the same as the laws of the communication of motion.'

It follows that the three laws of motion laid down by Newton, together with the principles applicable to the measurement of the action of force, should be studied most diligently by anyone who desires to understand the theory of heat.

HEAT IS PRODUCED BY THE AGITATION OF THE MOLECULES OF BODIES.

33. After the experiments of Rumford and Davy, the belief that heat was a material substance necessarily languished and died away, and the time has now come for stating more precisely the modern theory according to which the particles of all bodies by which we are surrounded are to be regarded as in a state of rapid and never ceasing agitation.

In order to present to the mind a 'sense-image' of the nature of heat, we begin by regarding all bodies as made up of assemblages of parts called *molecules.* A molecule may be of a complex character, consisting of distinct portions of matter held together by chemical bonds (as in the case of water, where a molecule is made up of separate parts of oxygen and hydrogen), and whatever may occur in the disposition of these separate parts or portions of matter, as to which we say nothing, it is agreed to call each whole collected mass a molecule, so long as its different portions do not break up and part company.

Heat is produced by the agitation or motion of the molecules of bodies. But the motion of heat is too minute to be recognised in any way by the senses, and cannot be detected by direct observation. It is evident, therefore, that very cogent evidence ought to be adduced before the new proposition is accepted. The doctrine of caloric may be untenable, and may have been demolished by experiment, but the student should nevertheless distinctly set before himself the question—How is a theory to be established which appeals for its support entirely to facts of observation, and which yet starts with the assumption that the thing to be made manifest to the mental vision exists in a region where no direct observation has ever yet penetrated?

Without doubt there is an enormous difference between the work of demolition and the work of construction. The former is comparatively easy, but the latter can only be arrived at by a slow and tedious process. Two decisive experiments abolished at once and for ever the theory supported by Black, but not one, nor two, nor one hundred isolated experiments can be appealed to as conclusively establishing Davy's proposition, and it is only by passing

over the whole domain of physical research that we meet with an aggregate of facts reconcilable with the one theory and irreconcilable with any other, and thus gradually yield to a conviction which it becomes impossible to resist.

Mr. Maxwell tells us ('Theory of Heat,' p. 306): 'The molecules of all bodies are in a state of continual agitation. The hotter a body is, the more violently are its molecules agitated. In solid bodies a molecule, though in continual motion, never gets beyond a certain very small distance from its original position in the body. The path which it describes is confined within a very small region of space.

'In fluids, on the other hand, there is no restriction to the excursions of a molecule. Hence in fluids the path of a molecule is not confined within a limited region, as in the case of solids, but may penetrate to any part of the space occupied by the fluid.

'A gaseous body is supposed to consist of a great number of molecules moving with a great velocity.

'The actual phenomena of diffusion both in liquids and in gases furnish the strongest evidence that these bodies consist of molecules in a state of continual agitation.'

THE CONVERSION OF WORK INTO HEAT.

34. In the year 1843 Mr. Joule made the following observation:—'When we consider *heat*, not as a *substance*, but as a *state of vibration*, there appears to be no reason why it should not be induced by an action of a simple mechanical character, such, for instance, as is presented by the revolution of a coil of wire before the poles of a permanent magnet.' Some striking experiments followed upon this suggestion, and it was shown that heat was actually induced in the manner anticipated. It is, however, not within the scope of this book to describe more than one illustration which has grown out of that originally suggested by Mr. Joule, and which powerfully confirms the belief that heat is caused by vibration.

In order to perform the experiment which we are about to describe, it is necessary to be provided with a very powerful electro-magnet and a whirling table, the arrangement being to bring the axis of the whirling table between the poles of the magnet and to

rotate at a high speed a small copper tube containing an alloy of metal which fuses at a low temperature. After three or four minutes of rotation the alloy melts, and may be poured as a liquid out of the tube.

The question then arises, what agency has been at work to fuse the metal. The heat is not traceable to direct friction, for the tube rotates in the empty space between the poles of the magnet and does not rub against anything. The effect must be in some way due to magnetism, for it is found that unless a battery current is sent through the coil of the magnet the rotation of the tube may go on as rapidly and as long as we please without producing any effect whatever. The tube remains perfectly cool, and there is no appearance of any heating action.

The connection between heat and work becomes apparent upon testing the increased exertion necessary for rotating the spindle of the whirling table while the metal is being heated. Before the magnetism is set up, a certain amount of effort is necessary in order to overcome the friction and inertia of the moving parts and to keep up the rotation. But the moment the magnetism is called forth, an increased resistance is felt, and a greater effort must be made in order to sustain the speed of the whirling tube. The additional work so demanded is passed in the form of heat into the tube. The conversion of work into heat is direct and palpable, but the precise nature of the molecular changes presents great difficulties. It will suffice here to point out that the experiment is based on an observed fact, viz., that when a flat blade or strip of copper is passed between the poles of an excited electro-magnet a resistance is felt, and if the blade be moved to and fro the sensation experienced is not that of moving through free air but rather of cutting through some viscous substance which clings upon the knife. It appears that the magnetism sets up an electric current in the strip of copper when its opposite ends are brought into contact, as they would be if the strip were bent round into a tube, and that new sets of particles come into action during the rotation. The resistance felt is exactly like that due to friction, but it is here not traceable to the rubbing of any material substances but rather to the indisposition of the metal to receive new currents of electricity induced by magnetic action and involving

sets of particles in which a new molecular motion is continually being set up, the disturbance caused thereby coming out as heat, and the work done being the increased effort made by the arm of the operator. The effect has been called by Dr. Tyndall 'friction against space.'

JOULE'S DETERMINATION OF THE MECHANICAL EQUIVALENT OF HEAT.

35. In a paper read before the Royal Society in 1849, Mr. Joule stated :—'From the explanation given by Count Rumford of the heat arising from the friction of solids, one might have anticipated as a matter of course that the evolution of heat would also be detected in the friction of liquid and gaseous bodies. Moreover there are many facts, such as, for instance, the warmth of the sea after a few days of stormy weather, which had long been commonly attributed to fluid friction. The first mention, so far as I am aware, of experiments in which the evolution of heat from fluid friction is asserted was in 1842 by M. Mayer, who states that he has raised the temperature of water from 12° C. to 13° C. by agitating it, without, however, indicating the quantity of force employed or the precautions taken to secure a correct result.' And he further said that he considered it of the highest importance to obtain the relation between force and heat with accuracy, and proceeded to describe the apparatus employed for that purpose as well as the mode of using it.

The apparatus employed for producing the friction of water consisted of a brass paddle-wheel furnished with eight sets of arms working between four sets of stationary screens attached to the inside of a copper cylinder, $7\frac{3}{4}$ inches in diameter and 8 inches deep. A facsimile model of the paddle and cylinder is deposited at South Kensington. The cylinder was covered by a lid having two necks *a* and *b*, the latter for the insertion of a thermometer, and the former being an opening for the axis of the paddle to revolve in without contact.

The general arrangement will be apparent from the sketch. The weights which rotated the paddle were each 29 lbs. (more accurately, 203,066 grains and 203,086 grains), and they fell through 63 inches at a rate of about 2·43 inches per second. Each weight

was attached by pieces of thin twine to a wooden roller A B, 2 inches in diameter, as shown, the roller being supported by steel axles $\frac{1}{4}$ inch in diameter, and running upon friction wheels. A wooden pulley, E, 12 inches in diameter and 2 inches thick, was also carried

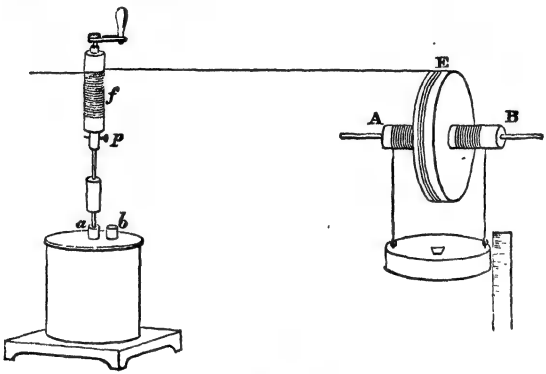


FIG. 20.

by the roller and was connected by a string to the small roller *f* on the axis of the paddle. The roller *f* could be fixed to the paddle axis by a pin *p*, or be disconnected at pleasure. While the friction was going on the paddle and roller revolved together, but they were disconnected by taking out the pin *p* as soon as the weights reached the ground, the roller being then supported in a movable frame while the weights were wound up ready for another descent.

The manner in which the friction of the water was set up will be apparent from fig. 21, which is a sectional elevation of the cylinder and paddle. The dark crossbars, two of which have square ends, are the paddles, and there is only just room for them to pass between corresponding openings in the fixed plate C D. A second plate, similar to C D, stands at right angles to it, and there are in all eight sets of paddles, whereby the drag upon the motion becomes very considerable. The plate C D is $7\frac{1}{2}$ inches wide and 7 inches deep.

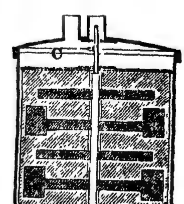


FIG. 21.

The laboratory was a spacious cellar, the temperature of which preserved a remarkable uniformity. The copper cylinder rested on a wooden stool, or rather grating, supported at some distance from the ground, and there was a wooden screen to protect the cylinder against any radiation of heat from the person of the operator.

Each experiment lasted 35 minutes, during which time the weights were allowed to fall twenty times in succession.

Two thermometers of extreme delicacy were employed, one, A, for reading the temperature of the water in the cylinder, and the other, B, for reading that of the air in the room. The space of 1° F. was subdivided into 12·951 divisions in thermometer A, and into 9·829 divisions in thermometer B, whereby Mr. Joule considered that he could estimate the temperatures to two-hundredths of a degree.

There were two classes of observations, viz.: (1) a frictional observation, wherein the total fall of the weights was recorded, as well as the temperatures of the water in the cylinder before the rotation of the paddle began and after it had ended. Thermometer B was also read at the beginning and end of the trial. (2) There was a so-called radiation experiment, intended to furnish an estimate of the probable passage of heat to or from the apparatus during the time of the frictional experiment. The nature of the observation is well given by Mr. Joule, who says:—'Previously to and immediately after, each of the experiments, I made a trial of the effect of radiation and conduction of heat to or from the atmosphere, in depressing or raising the temperature of the frictional apparatus. In these trials the position of the apparatus, the quantity of water contained in it, the time occupied, the method of observing the thermometers, the position of the experimenter; in short, everything with the exception of the apparatus being at rest, was the same as in the experiments in which the effect of friction was observed.'

Taking the fourth experiment as an example of what was done we find a tabulated result which is perfectly intelligible. The total fall in inches is recorded, and the word *friction* refers to the time when the paddle was in action, while the word *radiation* refers to the observations made in the next thirty-five minutes by starting at the temperature in the top line of column 6.

	Total fall in inches	Mean temperature of air	Difference between mean of cols. 5 and 6 and col. 3.	Temperature when experiment began	Temperature when experiment ended	Gain or loss
Friction .	1252·74	61·001	1·110	59·592	60·191	·599 gain
Radiation .	—	60·890	0·684	60·191	60·222	·031 gain
1	2	3	4	5	6	7

From a comparison of forty trials Mr. Joule deduced the numerical measure of the work done as being 6,067·114 foot-pounds, and inferred that the total rise of temperature in the water and copper was equivalent to a rise of ·563209 F. in 97,470·2 grains of water, or to 1° F. in 7·842299 lbs. of water. But

$$\frac{6{,}067{\cdot}114}{7{\cdot}842299} = 773{\cdot}64$$

Hence he deduced the mechanical equivalent of heat, as shown by the friction of water, viz. 773·64 foot-pounds in air, or 772·692 foot-pounds if the experiment had been conducted in a space freed from atmospheric air.

There were other experiments on the friction of mercury and cast iron, giving remarkable approximations to the above result, and Mr. Joule's paper ends with the following observations :—

1. 'The quantity of heat produced by the friction of bodies, whether solid or liquid, is always proportional to the quantity of force expended.

2. 'The quantity of heat capable of increasing the temperature of 1 lb. of water (weighed *in vacuo*, and taken at between 55° F. and 60° F) by 1° F. requires for its evolution the expenditure of a mechanical force represented by the fall of 772 lbs. through the space of one foot.'

THE KINETIC THEORY OF GASES.

36. Here it may be convenient to refer to the *kinetic* theory of gases, viz., the theory that a gas consists of a number of molecules, flying in straight lines, and impinging like little pro-

jectiles not only on one another, but also on the sides of the vessel holding the gas. *It is well known that a quantity of gas, however small, will expand and fill the whole of a vessel, however large; and further that it will exert some pressure upon its sides.*

Also, gases of every kind will diffuse into each other—a striking fact which may be illustrated by the following experiment. Fill two glass vessels, one with chlorine gas and the other with hydrogen gas, and connect them by a glass tube so that the hydrogen is uppermost. Chlorine gas is thirty-six times as heavy as hydrogen, yet in a few hours the gases will have diffused through both vessels, which will be filled with equal parts of chlorine and hydrogen.

The expansion and diffusion of gases are accounted for at once by the kinetic theory, and so is the law of Boyle, as well as a second fundamental law presently to be examined, and known as the second law of gaseous expansion. According to this theory the molecules should be pictured to the mind as endued with velocities somewhat greater than that of a rifle bullet, and thereby competent to rush into and fill an empty space with great rapidity.

Also, by continually rebounding from the sides of the vessel and from each other they keep up an incessant cannonade, and the aggregate of these minute blows is felt as a sensible pressure on the surface subjected to them. A bladder partly filled with air looks shrivelled, but when held before a fire it becomes hard and tense. The heat of the fire has given increased velocity to the molecules, and has enabled them to do more work. They discharge themselves with greater impetus against the inner surface of the bladder and overpower the bombardment from without. Presently their power becomes weakened by the increase of the area to be supported, and the bladder ceases to enlarge. As the air cools down the motion partially dies away and the bladder shrinks back to its original dimensions. It is thought that the velocity of a molecule of hydrogen at 32° F., and at the atmospheric pressure, is 6,097 feet per second. We have to take this theory with us to the consideration of the loss of heat experienced by a gas when doing work, and there can be no question that it enables the mind to grasp the fact with clearness. Add to which, that a general statement of the ideas now prevailing amongst certain writers is, at any rate, serviceable to the student.

THE SECOND LAW OF THE EXPANSION OF GASES: CHARLES'S, OR GAY LUSSAC'S LAW.

37. The expansion of gases under the action of heat is now to be discussed. Whatever view may be adopted to account for gaseous pressure, the fact of its dependence on temperature is thoroughly established, and such an illustration as that of the shrivelled bladder when partially filled with air becoming tense under the action of heat, is to be connected with a particular law known as the *second* law of the expansion of gases, and which was discovered by Charles, a professor of physics in Paris, some fourteen years before it was made public. It was published by Dalton in England in 1801, and by Gay Lussac in Paris in 1802, and is often called *Gay Lussac's law.*

The method of experimenting adopted by Gay Lussac will be understood from the annexed diagram.

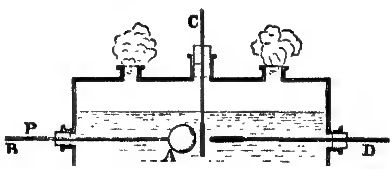


FIG. 22.

A certain volume of air, freed from moisture by passing it through chloride of calcium, was introduced into a thermometer tube having an enlarged bulb. A drop of mercury served both as an index and a valve, marking the expansion and separating the air within the tube from the external atmosphere. This air thermometer A B was then introduced into an iron vessel containing water and placed over a source of heat. The liquid was agitated, and two thermometers, C and D, marked the temperature. The drop of mercury P indicated by its position the volume of the enclosed air, both when the experiment began and when it terminated, the tube B A being drawn out through a water-tight collar and pushed in when necessary, so as to keep the mercurial index just outside the vessel.

The conclusions arrived at were the following :—

and shall endeavour to show that a mass of air may have its temperature lowered, not by the escape of heat according to the usual processes of conduction or radiation or convection, but in a totally different manner, namely, by allowing it to perform external work.

If we accept Davy's belief 'that the immediate cause of the phenomenon of heat is motion, and that the laws of its communication are precisely the same as the laws of the communication of motion,' there should be no hesitation in applying Newton's law that 'action and reaction are equal and opposite.' In doing so the result arrived at is no doubt startling. Granted that 772 lbs. (about $\frac{1}{3}$ of a ton) would, by falling through 1 foot, develop an amount of heat sufficient to raise 1 lb. of water through 1° F., it follows from the above law that the converse proposition should also be true, and that the heat necessary to raise the temperature of 1 lb. of water by 1° F. should be competent to lift 772 lbs. through a height of 1 foot. It does not appear that any direct experiment has ever established such a result, and it is difficult even to conjecture that it could be accomplished. Nevertheless our theory accepts the conclusion, and the failure is traced to practical difficulties. The student should therefore set before himself, as a model, an apparatus capable of converting heat into work according to the numerical result above stated, and should contrast the imperfect performance of actual practice with the imaginative working of an ideal engine where all imperfections or impossibilities of construction are supposed to be eliminated. By noting the degree in which the conclusions of theory exceed those actually reached, he will be working in a path which is continually leading to some improvement. Already important changes have taken place in the ideas which formerly prevailed among engineers as to the directions in which greater economy of fuel may be practicable.

41. We propose, in the first instance, to consider the performance of an ideal engine, where the material is such that no external heat can enter the working cylinder and no internal heat can pass away by the ordinary processes of conduction or radiation, and where the piston moves without any friction. Introduce now into the cylinder a mass of air at a high pressure and at a given

temperature, and allow it to expand doing work. Although the air enclosed can lose no heat by conduction or radiation, yet its temperature will rapidly fall as the expansion goes on. The walls of the cylinder present an impassable barrier to the transfer of heat according to the ordinary processes by which heat passes, but the engine is at work and there is no obstacle to the transfer of motion. If heat be motion, the machinery outside the cylinder cannot start into action unless the air within loses an exact mechanical equivalent in the agitation of its molecules, and it would be futile to expect that Boyle's law should be strictly fulfilled.

It is remarkable that Watt, in his patent of 1782, showed a working cylinder surrounded by a hot steam jacket, the direct tendency of which would be to preserve a constant temperature within, and to cause the expansion to follow the precise law laid down in his description of the invention.

In order to understand the matter more thoroughly it may be well to refer to some facts which have been observed in the application of compressed air engines. Taking the case of a compressed air engine set up at the Govan Colliery near Glasgow in 1849, it appears that a steam-engine was employed to compress air to a pressure of 20 to 30 lbs. per square inch. The air was then conveyed down a shaft 176 yards deep, and along a road through a further distance of 700 yards. The first difficulty arose from the heating of the compressed air in the cylinders of the compressing pumps, and layers of water covered the series of balls forming the piston and delivery valves, and thereby absorbed a quantity of heat as soon as it was generated. In recent engines, the flooding of the valves is not practised, but a horizontal compressing air cylinder has a water jacket open at the top in order to keep down its temperature.

According to the old theory it was believed that the heat fluid, or caloric, was squeezed out of a mass of air by sudden compression, and in this way the lighting of a piece of German tinder at the bottom of an air syringe by the sudden forcing down of the piston was commonly explained.

The development of heat by the act of compression being thus rendered apparent, we have to point out what takes place at the bottom of the mine where the compressed air does work in ex-

panding. The air engine referred to was an old high-pressure engine with a cylinder of 10 inches in diameter and 18 inches stroke, making about 25 revolutions per minute; and the next practical difficulty arose from the disappearance of heat in the working cylinder, whereby, on some occasions, the formation of ice in the cylinder and exhaust pipe clogged the working parts.

In order to meet the difficulty various suggestions have been made, and Mr. Siemens has pointed out that according to theory the better course would be to inject cold water, in the form of spray, into the compressing cylinder in sufficient quantity to keep the temperature practically uniform throughout the stroke; and afterwards, if such a thing were practicable, to take the very same water which had become heated in the compressing cylinder, and inject it again into the expanding cylinder, so that the heat taken from the air during the compression should be restored to it during the expansion.

UNIT OF HEAT AND FIRST LAW OF THERMODYNAMICS.

42. Adopting the belief that a quantity of heat means a quantity of molecular motion, the unit of measurement is the following:—

DEFINITION.—A *unit of heat* is the quantity of heat required for raising the temperature of 1 lb. of water, at or near its temperature of greatest density (39·1° F.) through 1° F.

The 'pound' here spoken of is the unit of mass, viz., the standard pound avoirdupois.

FIRST LAW. Heat and mechanical energy are mutually convertible, and heat requires for its production, or produces by its disappearance, mechanical energy in the proportion of 772 foot-pounds for each unit of heat.

The number 772 is usually denoted by the letter J, in token of Mr. Joule's experiment, and the temperature of the water referred to in defining a unit of heat is taken at 39·1° F. instead of lying between 55° F. and 60° F., as in the original experiment.

ON SPECIFIC HEAT.

43. The term 'specific heat' is used in a technical sense, for the word '*heat*' signifies *quantity of heat*, and *specific* means

peculiar to the substance. There must be some standard of reference in the measurement of specific heat, and the substance selected for this purpose is water at or near 39·1° F.

DEF.—The *specific heat* of any solid or liquid substance is the ratio of the quantity of heat required to raise the temperature of a given weight of the substance through 1° F., to the quantity of heat required to raise the temperature of an equal weight of water at 39·1° F. through 1° F.

Water is selected as a standard, because it opposes a greater resistance to a change of temperature than any other liquid or solid substance, and it follows that the specific heats of all solids or liquids are registered as fractions less than unity.

The specific heat of water is not absolutely constant, the specific heat of boiling water becoming increased by a minute fraction, and a progressive increase continuing at still higher temperatures.

In symbolical language it may be said that if q be the quantity of heat required to change the temperature of a given mass M from t to T, we should infer that q varies as $(T-t)$ when M is given, and that q varies as M when $(T-t)$ is given.

Hence $\quad q$ varies as $M\,(T-t)$,

$$\text{or} = c\,M\,(T-t),$$

where the constant c is called the *specific heat* of the substance, and is the measure of the quantity of heat which will raise the unit of mass through one degree.

44. In estimating the specific heat of a gas it is necessary to bear in mind the fact that the temperature of a gas is lowered by causing it to do work.

1. If a portion of gas be enclosed in a rigid vessel whose form is unalterable, and be heated, it does no external work, and its specific heat would be assigned just as in the case of a solid or liquid, that is, by comparison with water whose specific heat is unity.

The specific heat of air at a constant volume is ·169.

2. If a portion of gas be enclosed in a vessel in such a manner that it can expand under a constant pressure, and if it be subjected to the action of heat, it will increase in volume, and will push away any external air which presses upon it, thereby doing work.

The result is that it absorbs more heat in rising through a given number of degrees of temperature than it would do if no heat were converted into work.

The specific heat of air at a constant pressure is ·238.

The next step is to apply symbols to these results, and to certain calculations about to be given.

Let k be the specific heat of air at a constant pressure.

" c " " " constant volume.

Then $\frac{k}{c} = 1 \cdot 408 = \gamma$ suppose.

The ratio $\frac{k}{c}$ is of such frequent occurrence that it has been usual to designate it by a Greek letter γ.

The velocity of sound (in feet per second) in air at the temperature 32° F. may be proved to be $\sqrt{g \gamma \text{H}}$, where g is 32·2 feet, and H is 26,214 feet, the height, as it is called, of the homogeneous atmosphere at 32° F. The measured velocity of sound hence gives $\gamma = 1 \cdot 408$.

The value of k has been found by experiment, and (as stated) is equal to ·238, but the value of c cannot be ascertained by direct experiment, and is therefore deduced from the equation

$$c = \frac{k}{1 \cdot 408} = \frac{\cdot 238}{1 \cdot 408} = \cdot 169.$$

THE LATENT HEAT OF STEAM.

45. The principle successfully carried out in determining the temperature of high-pressure steam, has been also applied for determining the latent heat of steam.

The apparatus employed by Regnault (whose results are of the first authority) was too complex to admit of explanation here. A full account of it, together with an engraving of the several parts, is to be found in Jamin's 'Cours de Physique.'

Steam was generated in a boiler containing some 30 to 40 gallons of water, and was passed through a coiled pipe in the interior thereof before it was led away, the result being that any water adhering to the issuing steam was vaporised, and that the supply consisted of *dry saturated steam*. The pressure of the

vapour thus generated was determined by an artificial atmosphere, and was measured as in the previous case. There were two vessels, technically known as calorimeters, through each of which the steam passed twice for a few minutes, and wherein its latent heat was given up to a measured quantity of water. The annexed drawing shows the construction of one of the calorimeters employed. Steam enters the copper reservoir, C, which opens into a second reservoir, B. There is also a worm pipe passing from B, and twisted in a spiral round the inside of the calorimeter, but terminating in a pipe, D, leading to the receiver which regulates the pressure of the artificial atmosphere. A thermometer, T, gives the temperature of the water in the calorimeter. In order to preserve a continuous flow of steam through the apparatus at a time when the measurement is not proceeding, there is a condenser, into which the supply is turned at pleasure; also the pipe which leads from the boiler to the calorimeters is steam-jacketed throughout.

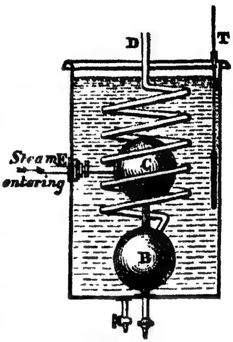


FIG. 24.

The results were, of course, given in graduations of the centigrade thermometer, and were as follows:—

1. The latent heat of steam produced at atmospheric pressure, or at a temperature 100° C., was represented by the number 537.

2. Taking the temperature of the steam at T degrees centigrade, it appeared that the quantity of heat necessary to raise a unit of weight of water from *o* to T and to transform it into vapour at a temperature T was equal to

$$606{\cdot}5 + {\cdot}305\ T$$

Since 537 C. = 966·6 F., we estimate that 966·6 units of heat become latent in the conversion of one pound of water at 212° F into one pound of steam at the same temperature.

Adopting now the graduations of the Fahrenheit thermometer, and remembering that 1° C. is equivalent to $\frac{9}{5}$° F., let L represent the latent heat of steam, and let H be its *total heat.* The designation 'total heat' is conventional, and is taken to express

the heat required to raise 1 lb. of water from 32° F. to the temperature of evaporation and afterwards to convert it into vapour,

$$\begin{aligned} \text{then } H &= 1091{\cdot}7 + {\cdot}305\,(t-32^\circ) \\ L &= 1091{\cdot}7 - {\cdot}695\,(t-32^\circ) \\ &= 1092 - .7\,(t-32^\circ) \text{ approximately;} \\ \text{or } &= 966 - {\cdot}7\,(t-212^\circ). \end{aligned}$$

Watt experimented on the latent heat of steam, and in 1781 estimated it by the number 950, but subsequently he put the numerical value a little higher, viz., at 960. Also, using the term 'free heat' to indicate the amount of sensible heat above 32° F. as measured by a thermometer, he enunciated the law that in steam at any given temperature—

Latent heat + free heat = a constant quantity. For example:—

	Units.	
One pound of steam at 212° F. .	180	sensible heat.
condensed at 32° F. gives out .	966·6	latent ,,
amounting together to .	1146·6	

Again—

	Units.	
One pound of steam at 250° F. .	218	sensible heat.
condensed at 32° F. gives out .	928·6	latent ,,
still amounting together to	1146·6	

But Regnault showed a variation from this law, and his formula gives 1158·2 as the total heat of steam at 250° F., instead of 1146·6.

It will be necessary to recur to this subject in the Appendix, where numerical examples and questions set in the Science and Art examination papers are brought together.

THE ABSOLUTE ZERO OF TEMPERATURE.

46. If air be adopted as a thermometric substance we commence our researches upon temperature in a very advantageous manner, for it is easy to conceive that the law of expansion of air is carried on indefinitely at increasing temperatures, and that the law of its contraction pursues an undeviating course as far as the point at which the whole of the heat contained in a mass of

air has been taken away from it. Then arises the question: What is the *real zero* of an air thermometer, or the indication which it would give if the air were deprived of all its heat?

In order to make the matter clear, let us take the case of air enclosed in a cylindrical tube of indefinite length, and separated from the atmosphere by a small globule of liquid which does not evaporate sensibly.

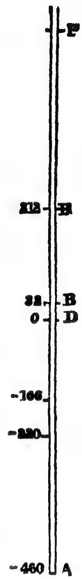


FIG. 25.

Let the tube A P be $60a$ inches long, and conceive that when the index is at B, marking 32° F., the length, A B, is $30\,a$ inches.

At 212° F. the index will rise to E, where A E is $41a$ inches.

Let x be the number of graduations in B P, when the index rises to P, such that A P $= 60a$.

$$\text{Then } \mathrm{BP} : \mathrm{BE} = x : 180^\circ$$
$$\text{or } \quad 30a : 11a = x : 180^\circ$$
$$\therefore 11x = 5{,}400^\circ$$
$$x = 491^\circ \text{ very nearly.}$$

Hence $30a$ inches is added to the tube of air by an increase of temperature of 491°; and, in like manner, $30a$ inches would be cut off by a fall of temperature of 491°. But that is the whole length of the tube, and it follows that the air cannot contract more than by a fall of 491°, or that the zero of the scale is 491° below B.

Hence D A $= 491^\circ - 32 = 459^\circ$.

The true value of the expansion is taken, however, to be ·3665, and not ·3666..., and consequently this number is slightly altered; so that whereas the bottom of the tube would be marked correctly at $-459^\circ.13$ F., it is usual to assign the number -460 F. as the zero of the scale.

This number indicates what is termed the *absolute zero* of temperature, and if the reading could be observed at the bottom of the tube it would imply that the volume of the air had been reduced to nothing. Mr. Maxwell says:—'If it were possible to extract from a substance all the heat it contains, it would probably still remain an extended substance, and would occupy a certain volume. Such an abstraction of all its heat from a body has

never been effected, so that we know nothing about the temperature which would be indicated by an air thermometer placed in contact with a body absolutely devoid of heat.'

If we agree to adopt the absolute zero of the air thermometer as the point at which the readings commence, and adhere to Fahrenheit's scale, we shall estimate freezing point, not as 32°, but as 32° + 460° or 492°. And like alterations for other temperatures.

On pausing to consider the amount of progress which has been made in travelling down the tube of an air thermometer towards the limit of the absolute zero, we shall find that hitherto the best results have been obtained by combining chemical with mechanical action. Thus Faraday obtained carbonic acid snow by allowing the substance when liquefied under pressure to escape into a small box, and the snow so formed could be wetted with ether, so as to produce a sort of paste having a temperature of −106° F. By accelerating the evaporation of the ether from this paste under the exhausted receiver of an air-pump the temperature was reduced to −166° F.

Natterer has obtained a still more intense degree of cold, by mixing liquid protoxide of nitrogen with bisulphide of carbon, and placing the bath in an exhausted receiver. By this process he has lowered the reading of a thermometer to −220° F.

The two laws of the expansion of gases, namely, the laws of Boyle and Charles, are connected together in a very simple manner under the view now suggested.

Thus if p, v, t represent the pressure, volume, and ***absolute*** temperature of a quantity of gas, then while t is constant, the product $p\,v$ is for this gas invariable. This is Boyle's law.

When t varies, $p\,v$ varies as t, or $p\,v = R\,t$, R being constant. This is the expression of the law of Charles or Gay-Lussac, whichever it may be called.

THE PROPERTIES OF AN ADIABATIC CURVE.

47. Another point for explanation is that there is a special curve which represents the expansion of a gas when confined in a vessel which possesses the imaginary property of not suffering any

heat to pass through its substance, and where the gas is doing external work during its expansion.

In such a case the curve of expansion will not follow Boyle's law, by reason that the temperature of the air will be affected through the interaction between heat and work.

For example, if the expanding gas does work, its temperature will fall by the conversion of the molecular motion of heat into the sensible motion of the mass upon which the work is done, and, since the pressure of a portion of gas is influenced by its temperature, the reduction of pressure will be greater than that exhibited by Boyle's law.

The curve of expansion is now called an *adiabatic* curve (from two Greek words, signifying not to pass through), and the name is intended to express the conditions under which expansion takes place, viz., that no heat passes out of the gas either by conduction or radiation.

The calculations necessary for determining the form of an adiabatic curve will now be given; but the processes cannot be made intelligible to students who are not conversant with mathematics, and the explanations in the next chapter are so framed that those who are unable to follow the symbolical reasoning may nevertheless take the results here investigated and apply them as required.

48. Prop.—To find the relations between the pressure, temperature, and volume of a portion of gas when it is expanded or compressed without addition or subtraction of heat.

Let p be the pressure, v the volume, and t the temperature of a given portion of gas.

$$\text{Then } p\,v = R\,t.$$

$$\therefore\ p\,d\,v + v\,d\,p = R\,d\,t. \quad (1)$$

As before, let k be the specific heat of the gas at a constant pressure, then the quantity of heat necessary to be given to a unit of weight of the gas without change of pressure, in order to increase its volume by $d\,v$ is

$$k\,.\,\frac{d\,t}{d\,v}\,.\,d\,v;$$

and if c be the specific heat at a constant volume, the quantity of

heat required to increase the pressure of the same portion by dp without change of volume is

$$c \cdot \frac{dt}{dp} \cdot dp.$$

If the variations of volume and pressure occur together, we adopt the principle that small increments from different causes may be superposed without interference, and the whole quantity of heat so required will be

$$k \cdot \frac{dt}{dv} \cdot dv + c \cdot \frac{dt}{dp} \cdot dp.$$

But, taking the equation $pv = Rt$, and differentiating, (1) when p is constant, (2) when v is constant, we have

$$\frac{dt}{dv} = \frac{p}{R} = \frac{t}{v},$$

$$\frac{dt}{dp} = \frac{v}{R} = \frac{t}{p}.$$

$$\therefore \text{ quantity of heat } = \frac{kt}{v} \cdot dv + \frac{ct}{p} dp = 0 \text{ by hypothesis,}$$

since there is no addition or subtraction of heat.

$$\therefore \frac{k\,dv}{v} = -\frac{c\,dp}{p}.$$

Substituting in (1) we have $p\,dv - \frac{kp}{c} \cdot dv = R\,dt = \frac{pv}{t}\,dt.$

$$\therefore -dv\left(\frac{k-c}{c}\right) = \frac{v\,dt}{t},$$

$$\text{or } -\left(\gamma - 1\right)\frac{dv}{v} = \frac{dt}{t}, \text{ since } \gamma = \frac{k}{c}.$$

$$\therefore \log\left(\frac{1}{v}\right)^{\gamma-1} = \log t + C.$$

Taking p_0, v_0, as values of the pressure and volume corresponding to a temperature t_0 we have

$$\log\left(\frac{v_0}{v}\right)^{\gamma-1} = \log\left(\frac{t}{t_0}\right),$$

$$\therefore \left(\frac{v_0}{v}\right)^{\gamma-1} = \frac{t}{t_0} = \frac{pv}{p_0 v_0},$$

$$\text{whence } \frac{p}{p_0} = \left(\frac{v_0}{v}\right)^\gamma, \text{ or } p\,v^\gamma = \text{a constant,}$$

which is the equation to the adiabatic curve.

Also the relations between the temperature, pressure, and volume of the enclosed gas are given by the equations

$$\frac{t}{t_0} = \left(\frac{v_0}{v}\right)^{\gamma-1} = \left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}}. \quad . \quad . \quad . \quad . \quad . \quad . \quad (2)$$

COR.—If $\gamma = 1$, the adiabatic curve passes into the curve $p\,v =$ constant, which is the curve of Boyle's law.

DIAGRAM OF AN ADIABATIC CURVE.

49. It is instructive to set out an adiabatic curve in a diagram, and to compare it with an *isothermal* curve, which follows the law of Boyle.

Let O M represent the volume, v_0, and P M the pressure, p_0, of a portion of gas at a temperature t_0. If the gas be compressed at a constant temperature t_0, we shall have R N representing the pressure at a volume O N and heat will escape. Whereas, if it be compressed to a volume O N without escape of heat, the pressure will be represented by Q N, as assigned by the previous calculation, and it is easy to see that Q N is greater than R N.

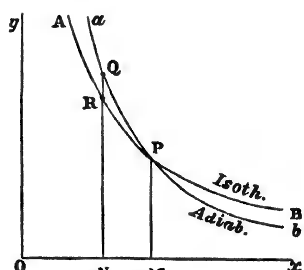


FIG. 26.

Also the temperature will rise from t_0 to t, as determined by the formula.

The conclusion is that air resists compression with greater power when the action is sudden, and the heat has no time to escape, than when it is gradual and the heat insensibly passes away. It is often said that a gas has two elasticities, viz., (1) the the elasticity at a constant temperature, (2) the elasticity when no heat escapes, and that we lose sight of the latter, which is the true elasticity, because it so rarely influences any observed result.

A remarkable illustration is afforded by researches on the velocity of the propagation of sound. The sound-waves compress and rarefy air suddenly. As stated by Mr. Maxwell:—'The changes of pressure and density may succeed one another several hundred times in a second, whereby the heat developed by compression in one part of the air has no time to travel by conduction to parts cooled by expansion, even if air were as good a conductor as copper is. But we know that air is really a very bad conductor of heat, so that in the propagation of sound we may be quite certain that the changes of volume take place without any appreciable communication of heat, and therefore the elasticity, as deduced from measurement of the velocity of sound, is that corresponding to the condition of no thermal communication.'

Newton calculated the velocity of sound by assuming that the elasticity of air followed Boyle's law, and made it less by one-sixth part than the observed result. The error was subsequently pointed out and corrected by Laplace.

'The ratio of the elasticities in the case of air, as deduced from experiments on the velocity of sound, is 1·408, which is also the ratio of the specific heat at constant pressure to the specific heat at constant volume.'

50. It may here be useful to point out one or two applications of the formulæ obtained.

Let a mass of air at volume 12, pressure 15 lbs., and temperature 60° F., be compressed without addition or subtraction of heat till its pressure rises to 30 lbs., the increase of temperature will be given by the formula,

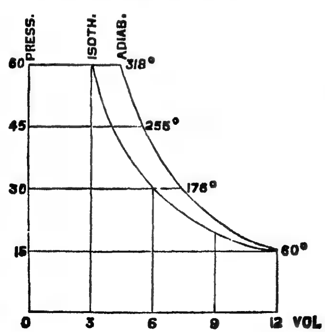


FIG. 27.

$$\frac{t}{t_0} = \left(\frac{p}{p_0}\right)^{\frac{\gamma - 1}{\gamma}}$$

But $\gamma = 1·408 \therefore \frac{\gamma - 1}{\gamma} = ·29$

Here $t_0 = 60° + 460°$
$= 520°$,

and $p_0 = 15$, whence temperature at pressure 30 pounds $= 520 \left(\frac{30}{15}\right)^{·29} = x$ suppose.

$$\therefore \log. x = \log 520 + \cdot 29 \times \log. 2.$$
$$= 2\cdot 7160033 + \cdot 0872987$$
$$= 2\cdot 8033020$$
$$= \log. 635\cdot 77$$
$$\therefore \text{temperature} = 635\cdot 77 - 460 = 176° \text{ F.}$$

In like manner the temperatures corresponding to pressures of 45 lbs. and 60 lbs. will be 255° F. and 318° F. respectively, the results being marked down in the annexed diagram.

51. To find the work done by a gas while expanding we proceed as follows :—

Adopting the previous notation, let w be the work done, and remembering that $p\,d\,v$ expresses the work performed in passing from v to $v + d\,v$, or is represented by the rectangle $s\,m$ referred to in Art. 18, we have to find the sum of all such rectangles analytically, which is done by integration, whence

$$w = \int p dv.$$

$$\text{But } p = p_0 \left(\frac{v_0}{v}\right)^{\gamma}$$

$$\therefore w = p_0 (v_0)^{\gamma} \int \frac{dv}{v^{\gamma}}$$

$$= \frac{p_0 v_0}{\gamma - 1} \left\{ 1 - \left(\frac{v_0}{v}\right)^{\gamma - 1} \right\}$$

$$\text{or} = \frac{p_0 v_0}{\gamma - 1} \left\{ 1 - \left(\frac{p}{p_0}\right)^{\frac{\gamma - 1}{\gamma}} \right\}$$

This formula may also assume the following shapes :—

$$w = \frac{p_0 v_0}{\gamma - 1} \left\{ 1 - \frac{t}{t_0} \right\}$$

$$= \frac{1}{\gamma - 1} \left\{ p_0 v_0 - pv \right\}$$

52. A comparison is often instituted between the relative advantages of compressed air or of water under pressure as a medium for the transmission of power to a distance. Those who advocate the use of compressed air, which is of great practical value in many cases, should nevertheless understand the penalty

which must be paid for the use of it. We are now in a position to calculate the loss of work due to the cooling of compressed air after it has been heated by the action of the compressing pumps.

Let a mass of air of volume v_0 and pressure p_0 be compressed to a pressure p, the work expended during its compression will be

$$-\frac{p_0 v_0}{\gamma - 1}\left\{1 - \left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}}\right\}$$

The temperature of the mass of air will be raised by this compression, and the simplest way of looking at the question will be to conceive that the air is allowed to cool at a constant pressure p, but contracting to a volume v.

Then $p_0 v_0 = pv$ by Boyle's law;

and work restored by the air when expanding behind a working piston

$$= \frac{pv}{\gamma - 1}\left\{1 - \left(\frac{p_0}{p}\right)^{\frac{\gamma-1}{\gamma}}\right\}$$

$$\therefore \frac{\text{work expended}}{\text{work restored}} = \left(\frac{p}{p_0}\right)^{\frac{\gamma-1}{\gamma}}$$

Ex.—Let $p = 3p_0$, or let the air be compressed to three times its original pressure,

$$\therefore \frac{\text{work expended}}{\text{work restored}} = \left(\frac{3p}{p}\right)^{\cdot 29} = 3^{\cdot 29}$$

$$\text{But } 3^{\cdot 29} = 1{\cdot}375,$$

$$\therefore \text{work restored} = \frac{1000}{1375} \times \text{work expended,}$$

$$= {\cdot}73 \times \text{work expended.}$$

That is to say, before any useful work is obtained from the compressed air, as much as 27 per cent. of the power has been thrown away. In tunnelling through the Alps, where the boring machines were worked by engines supplied from a reservoir of air at a pressure of six atmospheres, the loss by cooling amounted to about 40 per cent. of the power expended during compression.

CHAPTER III.

ON HEAT ENGINES.

53. A HEAT ENGINE, in the sense adopted in this book, is an apparatus for converting heat into mechanical work.

We purpose to discuss, in the first instance, the performance of an ideal heat engine, such that the curve of expansion of the working substance shall be an adiabatic curve.

On this hypothesis the working substance is a perfect gas, say air, enclosed in a cylinder provided with a piston capable of moving without friction. When the air is doing work, the material of the cylinder should be such that no heat can pass out of it and none can warm it. At other times it may be necessary for the air within the cylinder to accept or reject heat. The conditions for working are therefore contradictory, and accordingly, in the books on heat engines it is supposed that the piston, and the whole of the cylinder except its base, are perfect non-conductors of heat, while the base of the cylinder is a perfect conductor of heat, but yet has no capacity for heat, *i.e.* the amount of heat required to alter its temperature may be left out of consideration. Then there are two bodies A and B kept at different fixed temperatures, and there is a stand with a non-conducting surface on which the working cylinder can be placed when required. The engine is supposed to be placed on A when it takes in heat, to be carried to B when it gives out heat, and to rest on the stand when it works with the heat bound up in the enclosed gas. What is to become of the mechanism is not stated.

Under these circumstances it appears to be a waste of time to go through the formulary of supposing the engine to be actually at work, and shifted about during its performance. The whole

thing is the creation of the mind, and we shall disregard these details of supposed practice which clear up nothing, and shall merely conceive that everything takes place as required, so that the engine performs work in the manner intended.

Having thus settled the qualities which a heat engine should possess, we have next to ascertain what can be done with it.

The hypothesis being that a given mass of air is enclosed in the cylinder of an engine behind the working piston, it has been shown that if the air expands, doing work, its temperature will fall, not by conduction or radiation, but by reason of the conversion of heat into external work. The air inside the cylinder gives up part of its motion to the piston, and the fall of temperature is an interchange of motion and of nothing else.

DIAGRAM TO REPRESENT THE WHOLE WORK STORED UP IN A HEATED GAS.

54. Starting then with a mass of air at a volume v_0, a pressure p_0, and a temperature t_0, we observe that although it is impossible to predict anything as to its physical condition when approaching the temperature zero, yet we may assume that its pressure and temperature fall during the expansion of its volume according to the laws already discussed, whereby the shaded area

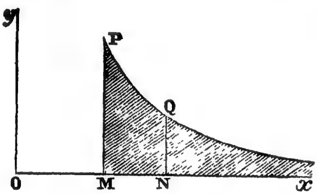


Fig. 28.

bounded on one side by the *adiabatic* curve P Q, represents the whole work capable of being yielded up during an indefinite expansion which finally depresses the temperature to the absolute zero.

Further the line O x is an asymptote to the adiabatic curve P Q, wherefore it becomes impossible to obtain the whole work theoretically bound up in the mass of air in question without carrying on the expansion till P Q meets O x, or until the volume becomes infinite. When that takes place, and not until then, will t become equal to zero.

At present we are engaged on a work of the imagination, and

have divested the problem of all practical difficulties, but it is nevertheless important to remember that an expansion down to 460° below zero in the Fahrenheit scale would be required in order to compel a mass of heated gas to yield up the whole of its molecular motion in the form of work. It is a common thing for people to say that 1 lb. of carbon, in burning, gives out heat enough to do the work of raising $772 \times 14{,}500$ lbs. through one foot, and they are apt to disregard the primary condition under which this performance would be possible. That condition is as hopelessly removed from our reach as if it were to be grasped only in some distant planet, and therefore it is better not to give any prominence to this mode of estimating the work stored up in fuel, but rather to think of it as a conception of the mind, and as something quite unreal.

MEANING OF THE TERM 'CYCLE.'

55. At this stage it will be convenient to introduce a technical word, namely, a *cycle*, and to explain the use made of it.

DEF.—A series of successive states of the volume and pressure of a working gas, which may be represented by a continuous line returning into itself, is called a *cycle*.

A cycle is *reversible* when the series of changes of volume and pressure can be passed through indifferently in either direction.

It should be understood that a cycle is the bounding line of some definite area, and the important consideration connected with it is that the area so enclosed represents either the external work done during the series of transformations by the enclosed gas; or, if not, it represents the work done upon the gas while carrying through these transformations in a reverse order.

Furthermore, by the first law of thermodynamics, heat and work are convertible the one into the other, whence it follows that the area enclosed by the cycle represents also the amount of heat expended in doing the work in question. This is universally true. If an area represents an amount of work done, it must also represent the quantity of heat expended in doing that work.

Referring to the diagram where the axes are the lines of

pressure and volume as in the previous cases, let the point P, whose position indicates the pressure and volume of a given quantity of gas at a given temperature, trace out the closed curve A P B P′. That curve will record the corresponding values of the pressure and volume of the gas at any instant, and is called a *cycle*. Also the area M A P B N represents the positive work done in passing through A P B, while the

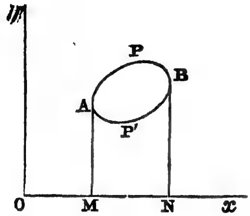


FIG. 29.

area M A P′ B N represents the negative work done in passing through B P′ A, the difference A P B P′ being the work done by the substance in undergoing the series of transformations.

The same area might also represent the work done upon the substance under altered conditions, and it necessarily represents the heat expended in the first case, or that absorbed on the alternative supposition, viz., that work is done upon the substance.

DIAGRAM OF HEAT ABSORBED OR REJECTED BY A PORTION OF GAS IN PASSING FROM ONE TEMPERATURE TO ANOTHER.

56. Let O v, v T represent the volume v, and pressure p of a portion of a gas (say air), at a given absolute temperature T, and draw the adiabatic curve T T′ R. Let the air expand doing work, to a pressure v' T′ and temperature T′. Then lower its temperature at a constant volume O v', till its pressure falls to t' v', and its temperature to t'. Compress the air to its original volume O v, as shown by the adiabatic curve t' t, when its temperature will rise to t (suppose), and finally heat the air at a constant volume O v, till its temperature rises again to the original value T. This will form a complete cycle of operations, and, according to the principle laid down, the work done by the air during the cycle will be represented by the area T T′ t' t.

Referring to the diagram where O x represents the line of volumes, and O y the line of pressures, we observe that the two adiabatic curves approach indefinitely near to the line O x as the expansion goes on, and therefore also they approach indefinitely

near to each other. But the air gains heat in passing from t to T, and loses heat in passing from T′ to t', and it is apparent that as the expansion goes on this lost heat is continually becoming less and less and finally vanishes, wherefore the whole heat absorbed in passing from t to T is represented by the indefinitely prolonged area T R S t, bounded by T t and the two adiabatic curves T R, t S.

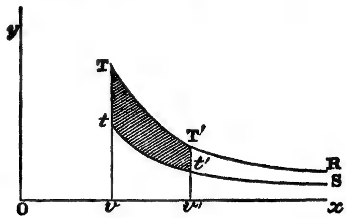


FIG. 30.

This conclusion follows, indeed, as a corollary to Art. 54.

In like manner if the volume and pressure be caused to vary in any arbitrary manner between the points A and B, as shown by the curve A D B, and the adiabatic lines B R, A S, be drawn as before, the shaded area A D B R S will represent the mechanical equivalent of the heat absorbed or given out by the substance in passing from the state A to the state B, or conversely.

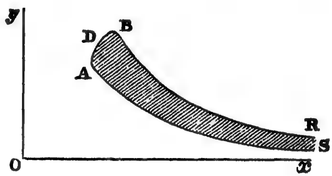


FIG. 31.

HEAT ENGINE WORKING BETWEEN TWO FIXED TEMPERATURES.

57. It is the property of an engine that it must continually get back to a starting-point, and go through all its operations over again, and of course it becomes necessary at once to abandon all idea of obtaining the work represented by the indefinitely prolonged strip A B R S. A heat engine can only operate in a closed cycle such that the working substance reverts continually to the volume, pressure, and temperature which it had at starting. All that we can hope for is to obtain as large a slice of the strip A B R S as may be practicable under the conditions of expansion which the construction of the engine will permit. The method will be to travel a certain distance down the adiabatic curve T R, then to cross over to another adiabatic curve S t, to pursue an upward path through a certain space, and finally to return in some convenient manner to the starting-point. Our hypothesis shall be

that the engine works between two fixed temperatures T and *t* (T being the greater), and that the working substance, say air, takes in a quantity of heat H at the higher temperature T, and rejects a quantity *h* at the lower temperature *t*, and performs external work under these conditions.

The cycle of operations will be the following :—Starting from the point T in the adiabatic curve C S, the air expands through T T according to Boyle's law, remaining at a fixed temperature T and

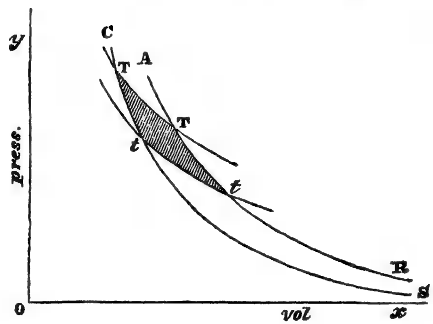


FIG. 32.

taking in a quantity of heat H. It then expands through T *t* along the adiabatic curve A R, doing work, and falling from a temperature T to *t*. It is next compressed along *t t* at a constant temperature *t*, giving out the quantity of heat *h*, and finally it is compressed along the adiabatic curve S C from *t* to T, and returns to its original volume, temperature, and pressure.

The enclosed shaded area is the indicator diagram of the engine, and gives a measure of the work done, or equally, of the heat converted into work.

In truth, the heat taken in along the curve T T is represented by the indefinitely prolonged area T T R S, while that rejected along *t t* is given by *t t* R S, the difference between the two areas marking the conversion of heat into work.

The problem now in view is to find some relation between (H, *h*) on the one hand, and (T, *t*) on the other hand.

Let it be granted, as there is no reason to doubt, that if the absolute temperature of any uniformly hot substance, such as the

working gas or air, be divided into an indefinitely large number of equal parts, the effect of each of those parts in causing work to be performed will be the same; and it will follow that if t T be made very small at any temperature t, however selected, the area T T t t will always bear to the whole area t t R S the same proportion which T t bears to t.

In other words if q be the quantity of heat represented by the area t t R S, and dq that represented by T T t t, the alteration from t to T being represented by dt, we shall have

$$\frac{dq}{q} = \frac{dt}{t}.$$

or $q = \text{A}\, t$, where A is a constant.

That is the same thing as saying that

$$\frac{\text{H}}{\text{T}} = \frac{h}{t},$$

a fundamental relation which is of the greatest possible use in this theory, and which has been shadowed forth throughout the reasoning of the previous pages.

It is material to comprehend the exact agency of the heat consumed in the operations, and we note that the heat H is taken in while expanding according to Boyle's law, and that the heat h is given out during a like compression.

In order to estimate the work done we proceed as follows:—

Let J represent Joule's equivalent, or 772 foot-pounds.

The quantity of heat H is capable of doing the work J H, and in like manner the quantity of heat h can do the work J h.

$$\therefore \text{ work done by the engine} = \text{J}\,(\text{H}-h) = \text{J H}\left(1-\frac{h}{\text{H}}\right).$$

$$\text{But } \frac{h}{\text{H}} = \frac{t}{\text{T}},$$

$$\therefore \text{ work done} = \text{J H}\left(1-\frac{t}{\text{T}}\right) = \text{J H}\left(\frac{\text{T}-t}{\text{T}}\right).$$

Conceive that an ideal engine worked with air heated up to 300° F. and cooled down to 50° F., we should have

$$\text{T} = 460 + 300 = 760,$$
$$t = 460 + 50 = 510.$$

$$\therefore \text{ work done} = \text{J H}\left(\frac{760-510}{760}\right) = \frac{1}{3}\,\text{J H, very nearly.}$$

That is to say, our ideal engine, which is absolutely faultless in construction, and therefore unattainable, cannot reproduce, under the assigned differences of temperature, so much as $\frac{1}{8}$ of the work which is stored up in the mass of heated air. A practical mechanic who is concerned at the statement that the modern steam-engine is full of glaring defects, may derive some consolation from an accurate definition of the limits within which improvement is possible.

It is hardly necessary to point out that the cycle of operations is reversible. Thus we may start from the point T in the line C S, travel down T t doing work, cross over through t t taking in a quantity of heat h, then rise through t T doing work upon the air, and pass through T T giving out a quantity of heat H. The work done upon the enclosed air would therefore be represented by J (H $-$ h).

58. As an example of a cycle which is not reversible, take the indicator diagram of an ordinary condensing engine as given by theory.

The steam is supplied at a uniform pressure along A B, it expands and does work along B C, its temperature and pressure fall suddenly as shown at C D, and its pressure remains constant through D E.

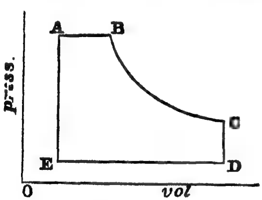


FIG. 33.

In the reverse operation the steam and condensed water should be compressed till its pressure rises through D C, and the water into which the steam has been condensed should be reconverted by pressure into steam at the temperature at which the expansion during the direct working came to an end. This is an impossibility, and an ordinary condensing engine is therefore non-reversible.

ELEMENTARY HEAT ENGINE.

59. It is convenient to distinguish by a particular designation an engine which works under the three conditions now to be enumerated, viz., that

1. All the heat is taken in at a higher constant temperature T.
2. All the heat is rejected at a lower constant temperature *t*.
3. The cycle is reversible.

When an engine fulfils these conditions, it is termed an *elementary heat engine*, and enjoys the property that it cannot be surpassed in efficiency by any other engine working between the same temperatures; it is, in fact, an ideal perfect engine, and is the model instituted for mental comparison in viewing the performance of real engines.

CARNOT'S PRINCIPLE.

60. At this stage we propose to discuss the principle laid down by Sadi Carnot in 1824. Carnot, who was a French officer, and son of the celebrated Minister of War under Napoleon, founded his theory of heat engines on the erroneous supposition that heat was a substance, but his errors were those of a man of genius, and the principle which he enunciated is a fundamental truth according to the dynamical theory. Writers on the subject of heat tell us exactly where Carnot was right, and where he was in error, and they distinguish and analyse his statements. In the present treatise we shall not attempt to follow them, and shall merely refer the student to other sources, such as Maxwell on 'Heat,' for information on this point.

Carnot's book was entitled 'Reflexions sur la puissance motrice du feu, et sur les machines propres à développer cette puissance,' and the idea firmly fixed in the mind of the writer was that the performance of work should be attributed solely and absolutely to the agency of heat.

The principle of Carnot may be stated as follows:—The amount of work done by a reversible heat engine depends only on the constant temperatures at which heat is received and at which it is rejected, and is independent of the nature of the intermediary agent (such as steam, air, &c.).

This principle involves two propositions which are sufficiently striking, and the first is that the elementary heat engine heretofore discussed, and which took in heat at one constant temperature and

sion, that passes without any contest, the whole theory of heat engines is based upon expansive working. And here it may be instructive to review the progress made by engineers in the use of high-pressure steam without reference to the doctrine that heat alone is the agent which does the work.

It has been stated in Art. 21 that Hornblower invented the double or compound cylinder engine for expansive working, and that he intended, as did Watt in his patent of 1782, to employ steam at or near the atmospheric pressure. The economy resulting from the expansion of steam at a high-pressure was, however, first insisted upon by A. Woolf, a Cornish man, who converted Hornblower's double cylinder engine into a form suitable for driving machinery (see Chapter VII.), and erected a so-called Woolf's engine working with high-pressure steam and condensation at Meux's Brewery in 1806. Woolf entertained the most fanciful and erroneous ideas as to the power of high-pressure steam when expanded, but, although quite wrong in his theory, he persevered in the construction of his engines, and erected several which worked with steam at a pressure of from 40 to 60 pounds above the atmospheric pressure. Down to the year 1814 the pressure of the steam in Cornish engines never much exceeded that of the atmosphere, and at this low initial pressure there was practically but little economy resulting from expansive working, whereby it appears that after Watt's immediate connection with the mining district ceased, expansion fell rapidly into neglect. Then it was that R. Trevethick and Woolf both advocated in Cornwall the economy of high-pressure steam with expansion, a mode of working which was applied by the former in Watt's single cylinder engine and by the latter in the double cylinder engine.

It was indeed proved that, by the new method, it was possible to raise the duty of an engine (see Chapter V.) from 20 millions of foot pounds for one bushel of coal (94 lbs.), at which Watt had left it, to 50 or 60 millions of foot pounds. This was an extraordinary result, and the only question that arose related to the manner in which the principle should be carried out. At the present day there are often long discussions as to the comparative value of one or two cylinders for expansive working, but in Cornwall the practice soon settled down into that which has been maintained

ever since, viz., the use of a single cylinder engine with steam at a pressure of some 30 lbs. above the atmosphere, and cut off at $\frac{1}{4}$th or $\frac{1}{5}$th of the stroke.

Note.—In practice, steam at 30 lbs. pressure means 30 lbs. above the atmosphere, unless the contrary be expressed. In theory, it means 30 lbs. *actual* or *absolute* pressure, giving an effective pressure of 15 lbs. approximately.

1. It is now worth while to apply our conclusions as to the efficiency of a heat engine to the case of expansive working, under Watt in the first instance, and afterwards under Woolf or Trevethick.

Watt used steam at atmospheric pressure and condensed at a temperature of 100° F. He expanded it (say) four times.

At that time there was no numerical measure of the conversion of heat into work, and the idea of regarding the higher temperature of denser steam as entering at all into the question of its economy as an agent was not entertained by any engineers. It was enough to be satisfied that additional work was obtained from the steam before it was thrown away.

Theoretically, in a heat engine, the working substance should expand from the temperature of the source of heat to that of the refrigerator, in this case the condenser. That would require, for steam falling from 212° F. to 100° F. an expansion to about fifteen times the original volume, which of course was impracticable.

Taking that expansion as accomplished, we should have $T = 212 + 460 = 672$, and $t = 100 + 460 = 560$.

$$\therefore \text{ greatest work possible} = JH\,\frac{112}{672} = JH \times \frac{1}{6} \quad . \quad . \quad (1)$$

2. Taking a Woolf's engine working with steam at 45 lbs. actual pressure, *i.e.* at a temperature of 274° F., and condensing at 100° F., as before. The expansion should now go on to about 45 times, and if that were possible we should have

$$\text{work done} = JH\left(\frac{734-560}{734}\right) = JH \times \frac{4}{17} \text{ nearly} \quad . \quad . \quad . \quad (2)$$

Referring to Chapter V., we find that with ordinary coal JH represents a consumption of $\frac{1}{4}$ lb. of coal per H.P. per hour; hence the above results are (1) $1\frac{1}{2}$ lbs. of coal per H.P. per hour; and (2) $1\frac{1}{18}$ lbs. of coal per H.P. per hour.

These examples show unmistakably that theory soon leaves practice far behind. They are inserted solely with the intention of exhibiting the subject from a modern point of view.

After reviewing the theory of heat engines it must appear to be a remarkable thing that the progress in the use of high-pressure steam with expansive working and condensation should have gone on so slowly.

In the year 1817 marine engines were worked at a pressure 3 to 5 lbs. above the atmosphere. In that year an engineer giving evidence before a Select Committee on Steamboats took it for granted that cylindrical boilers would not be used in steamboats, because, as he put it, the most convenient form of the boiler was one adapted to the shape of the boat, and the safety depended upon the strength of the metal and not upon the form. The committee had been appointed in consequence of the explosion of a boiler using high-pressure steam on board a vessel at Yarmouth; the boiler was cylindrical, with a flat cast-iron end, which gave way. Other engineers who were examined were of opinion that the steam-pressure in a boiler should not exceed 6 lbs. above the atmosphere, and further, that there was no saving to be effected by employing a higher pressure.

When screw ships were adopted in the navy, one of the first of the new series of vessels, the 'Arrogant,' was designed to work at 6 lbs. steam pressure; but the ship was deep in the water, and the boiler would not blow off under 7 lbs. It appears that Mr. Penn soon went to 10 lbs. and then to 14 lbs. But boilers for 14 lbs. nominal pressure were capable of supporting 20 lbs., and the usual average of pressure came to be about 16 to 17 lbs.

Within the last 15 years, however, a great change has occurred in the construction of marine engines, and it is shown from the tabulated results furnished by Mr. Bramwell in a paper on the progress effected in economy of fuel in steam navigation, which is particularly referred to in Chapter VII., that the advantage of using steam at a high pressure, with an early cut-off, and as perfect condensation as can be obtained, is now thoroughly recognised. Mr. Bramwell gives the experience of 19 engines of ocean steamers, with high and low pressure cylinders, working at a steam pressure of from 45 to 60 pounds in the boiler with a consumption of coal

certainly less than one half that which commonly prevailed in the days of single cylinder engines with low-pressure steam and very moderate expansion. In like manner the practice with stationary engines has improved, so that it is common to hear of engines with compound cylinders using steam at 70 to 80 lbs. pressure, and consuming $\frac{1}{3}$ or $\frac{1}{4}$ less coal than was formerly required for obtaining the same amount of work.

ON AIR ENGINES WORKING WITH A REGENERATOR.

63. Having investigated the conditions under which an ideal heat engine exhibits the greatest efficiency, whereof one is that all changes in temperature of the enclosed air shall be caused solely by compression or expansion, we may remark that, in the present state of knowledge, no method has been proposed whereby the conclusions of theory can be successfully carried out, the enormous dimensions which the cylinders would assume presenting insuperable difficulties.

But although the practical obstacles which stand in the way cannot be overcome, they may be evaded by a method which permits of a deposition and a taking up of heat within the interior of the engine itself, so that none is lost, the result obtained being much better than would probably have been anticipated.

The artifice consists in the use of a so-called *regenerator* (said to have been invented by the Rev. R. Stirling), which is an apparatus employed in various forms, and which was described by J. & R. Stirling in the specification of a patent (A.D. 1827, No. 5,456), for improvements in air engines for working machinery.

The principle of a regenerator is perhaps most readily exhibited by the safety-lamp of Sir H. Davy. It is well known that if a piece of wire gauze be brought down upon the flame of a candle the flame will be cut off at the part where it touches the gauze. The explanation is that the meshes of the metal wire have robbed the gases of so much heat as to lower their temperature below the point at which ignition is possible. They are not otherwise affected, and may be at once rekindled on presenting a flame at the upper surface of the gauze.

In its earliest form the Davy lamp was an ordinary lamp,

having the flame encased in a cylindrical covered chimney of wire gauze. By multiplication of the layers the effect is heightened, and we arrive at a respirator for filtering out heat from a warm current of air, and heating up a current of colder air sent through in the opposite direction.

The principle here set forth has also been applied in the construction of furnaces, where a regenerator is composed of a number of open fire-bricks, exposing a large surface for the absorption of heat. In such a case the products of combustion from the furnace gradually deposit their heat before escaping into the chimney, and the end of the regenerator nearest to the furnace reaches a very high temperature, while the chimney end remains comparatively cool. The direction of the draught is now reversed, and the air for supplying combustion in the furnace is drawn through the heated regenerator, while the waste gases are led into a second cool regenerator, in order to yield up their heat in the manner already described. By alternating the current between the two regenerators a great saving of fuel is effected, for the furnace is supplied with heated air, and the escaping gases deposit a large amount of heat, which is carried back to the fuel instead of being wasted.

The regenerator of a Stirling engine was intended to raise and lower very rapidly the temperature of a mass of air, and the substance employed for the purpose was the thinnest sheet-iron. The area of surface exposed was very large, amounting to as much as 3,200 square feet in an air engine of 45 horse power. A number of strips of sheet-iron, each 38 inches long and $1\frac{3}{4}$ inches broad, and of a thickness of $\frac{1}{50}$ inch, were arranged side by side at intervals of $\frac{1}{50}$ inch. The narrow passages between the strips formed channels through which the air passed in alternate directions. If a regenerator were formed of sheets of wire gauze placed parallel to each other and separated by non-conducting material, it would be easy to conceive that each plate might preserve its proper temperature, but where the air passed through continuous metal channels it might be thought difficult to maintain one end hot while the other was cold. With one engine making about 30 strokes per minute, it did not appear that the loss by conduction was serious, but the specification of a subsequent

patent of 1840 (No. 8,652) for an improved air engine described the plates as divided into four or more portions, the object being 'to diminish their effect in conducting heat from the hot to the cold part of the plate-box.'

64. Two engines have been constructed on Stirling's principle, and have worked with considerable success. The first had a cylinder 12 inches in diameter, with a 2 feet stroke, making 40 revolutions per minute, and giving out 21 H.P. The consumption of coal was $2\frac{1}{2}$ lbs. per H.P. per hour. Subsequently an engine of 45 H.P. was set up at the Dundee Foundry, and drove all the machinery of the works for a period of three years. The cylinder was 16 inches in diameter, with a 4 feet stroke, and the number of revolutions was about 28 per minute. The heating vessels, however, caused so much difficulty that the method was given up.

DESCRIPTION OF STIRLING'S AIR ENGINE.

65. Stirling's engine is supplied with compressed air; that is an essential condition, for otherwise the power developed would be insufficient to move the working parts. In one example the pressure of the air varied from 160 lbs. to 240 lbs. per sq. inch, the temperature rising to 650° F. on one side of the regenerator, and falling to 160° F. on the other side.

The appearance of the engine is that of an ordinary steam engine, the usual steam cylinder being converted into an air cylinder. Two cylindrical air vessels are connected with the working cylinder, one at each end thereof, and they perform the double office of a slide valve and boiler. They are of considerable size, being more than five times as large as the working cylinder; and it is stated that $\frac{5}{8}$ of each air vessel is occupied by its plunger, which is a hollow vessel, also cylindrical, turned so as to fit the interior of the air vessel quite closely, but without friction, and having a quantity of brickdust or other slow conductor of heat at its base.

The drawing shows a section of the air vessel A B, with its plunger K H; both are formed of cast iron, and the object is to obtain a very close fit between the plunger and the cylindrical

casing, so as to prevent as far as possible any leakage of air along its sides. The bottom of the plunger is lined with brickdust, and a pipe leads from the space K B to a box E F, containing the regenerator. Two-thirds of this box is filled with plates of sheet-iron, and the remainder is filled with a number of copper pipes $\frac{1}{8}$ inch internal diameter, and $\frac{1}{16}$ inch thick, through which cold water circulates. The pipes are at a distance of $\frac{1}{20}$ inch apart, and form a refrigerator for removing any heat which has not been previously extracted by the cold end of the regenerator. Any empty space round the pipes may be filled with blocks of iron or brass. The plate box terminates in an open pipe E M leading to the working cylinder. A fire is kept burning under the bottom of the air vessel, which is of increased thickness at the base. There is a compressing pump for supplying any waste of air by leakage, the usual pressure of the enclosed cold air being ten atmospheres.

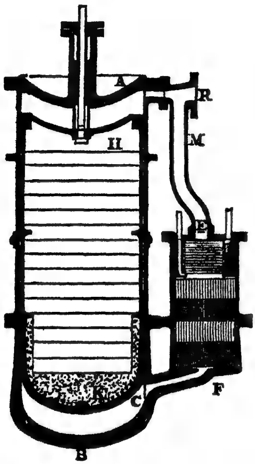


FIG. 34.

When the plunger is raised it sends a quantity of air from the top of the air-vessel through the regenerator into the space K B. The air in K B is heated not only by passing through the hot end of the regenerator, which is at its base, but also by the heat of the fire; its pressure rises, and it expands so as to produce an increased pressure along the passage R, which is at once felt upon one side of the piston in the working cylinder. On the other side of this piston is a second similar air-vessel, with its plunger depressed, whereby heated air has been forced through the regenerator into the space corresponding to A H, and has been cooled to a lower temperature and pressure, thereby causing the pressure on its side of the piston to fall, and the result is that we have air at, say, 240 lbs. pressure on one side of the piston, but at 150 lbs. pressure on the other side, and that there is an ample amount of working power. The peculiarity of the engine is

that the enclosed mass of compressed air is divided into two distinct portions, A and B, which are in some sense separate, although an open passage leads always from one to the other.

The mass of air A fills the air vessel and passes to and fro through the regenerator. It is heated and cooled alternately, and the changes in its temperature give rise to the work done. The mass of air B is in contact with the piston of the engine; and since B and A open freely to each other, the pressure of the mass B rises or falls with the pressure of the mass A. But that is all, for B is a mere carrier of pressure to the piston of the engine, and its temperature is comparatively unaffected.

As to the mechanism of the engine, that is the same as for an ordinary steam engine. The only point to be noticed is that the plungers of the two air vessels are first worked by hand, in the same manner as the valves of a steam engine, and that after the engine is fairly started the motion is continued by an eccentric on the fly-wheel shaft.

66. It may be useful to give the type of the diagram of energy in Stirling's engine, although the subject demands much more space than is available in order to examine it thoroughly. Starting from the point S, with a mass of air at volume O M, and pressure S M, and remembering that we are not now dealing with the working cylinder—for the primary effect is modified by the cushion of air, so that the diagram in the cylinder would be somewhat as if that now to be exhibited were drawn on an elastic sheet of indiarubbe and pulled out at two opposite corners—we proceed as follows:—

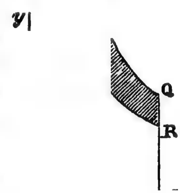


FIG. 35.

1. The air takes up heat in passing through the regenerator, and its pressure rises to P M.

2. The air expands along the isothermal curve P Q, for the loss of heat in doing work is at once repaired.

3. The air deposits heat in the regenerator, and its pressure falls from Q N to R N.

4. The air is compressed along the isothermal curve R S, for the heat given out in compression is at once absorbed.

The shaded area P Q R S is the diagram of energy, and we see that by the artifice employed the engine works approximately according to the figure given above, but only approximately, for the heating or cooling does not take place exactly at a constant volume, and does not affect more than a portion of the enclosed air, nor do the expansion and compression occur exactly at constant temperatures.

It does not appear that a heated air engine with a regenerator has ever taken root, but the principle is established, and accordingly the reversible quality of such an engine has been successfully applied to that which is somewhat misnamed by its advocates, viz., the so-called 'mechanical production of cold.'

67. In a reversed Stirling's engine the working cylinder is converted into a pump driven by external force, and the cool end of each air vessel receives a substance from which heat is to be abstracted. Referring to fig. 35 we find that—

1. The air is compressed through Q P, and its temperature rises.

2. Heat is then abstracted by a refrigerator cooled by a current of cold water, and further by a regenerator, the pressure falling to S M.

3. The air expands through S R doing work, losing temperature, and taking up heat from the substance to be cooled.

4. It is passed through the regenerator, becoming warmed, and its pressure rises to Q N.

This cycle is continued, and at each double stroke of the pump a portion of heat is taken from the substances in each air vessel which are undergoing the cooling process, and is deposited in the regenerator, and this goes on until such a difference of temperature is set up between the hot and cold ends of the absorbing surfaces that the heat taken away from the substances is continually restored by conduction through the material of the regenerator.

In a working engine it has been found that this result takes place at a temperature of 50° to 60° below the zero on the Fahrenheit scale.

CHAPTER IV.

ON THE CONVERSION OF MOTION.

68. JUST as it is necessary to know something of the theory of heat in order to understand the philosophy of the steam engine, so also it is essential to pass through some training in the elements of the conversion of motion in order to comprehend the mechanism of the moving parts. We propose in the present chapter to give a brief outline of certain fundamental propositions which will be useful.

The belief held by the ancients as to the nature of circular motion was fanciful in conception, and was obviously untenable. It was said that motion in a circle was *simple*, in the sense that it was a primary movement, and not made up by putting together other separate movements. We, on the other hand, hold that the only case of simple motion is that of a point describing a straight line with a uniform velocity. Whenever a point deviates from a rectilinear path it is, or may be, the subject of two independent movements in lines at right angles to each other.

It is upon this idea that the whole learning of analytical geometry is built up. If we wish to represent a curve by means of a relation between symbols, called an *equation to the curve*, we begin by drawing two lines, $x\,O\,x'$, $y\,O\,y'$, at right angles to each other, and employing them as lines of reference.

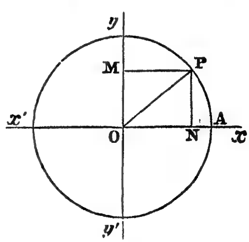


FIG. 36.

For example, let the curve be a circle whose centre is the point O.

Take P, any point in the curve, and draw PN perpendicular to Ox. Let $ON = x$, $NP = y$, $OP = a$.

$$\text{Then } ON^2 + NP^2 = OP^2; \text{ or } x^2 + y^2 = a^2,$$

a relation between x, y, a which is satisfied by points situated in the circular curve A P, and by none other, and which is therefore called the equation to the curve.

The lines x, y are the co-ordinates of the point P, and the axes $x\,O\,x'$, $y\,O\,y'$ are the axes of co-ordinates. Also the signs + and − are employed to indicate the position of P in any particular quadrant; thus, if P were situated anywhere in the quadrant $x'\,O\,y'$ the corresponding values of x and y would both be negative.

It is to be observed that when P starts from A and travels round the circle, the point N follows this movement and makes an excursion from A to B and back again from B to A (see fig. 38). In other words, N makes a complete double oscillation in the line A B, while P describes the circumference of the circle.

In like manner if we draw P M perpendicular to O y, we shall find that M makes a complete double oscillation in the line $y\,y'$, while P describes the circumference beginning at A and ending there again. And yet there is a marked dissimilarity, as well as a resemblance, between the movements of N and M, which should now be made clear.

69. Referring to the drawing, which is sketched from a model intended to exhibit simultaneously the motions of the points M and N, the framework being left out, we have a pin P passing through the grooved bars R S and T V, which overlap each other, and are connected by slender rods sliding between guides. Also x and y are small balls or index fingers traversing over a graduated scale, and indicating the movements of the respective bars. As the pin P travels round a circular groove A P B E formed in a board, it is apparent that x will oscillate to and fro with a motion identical with that of N, and that y reproduces the movement of M.

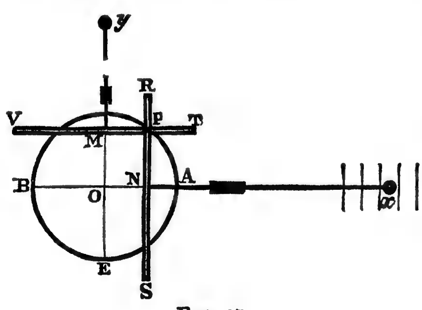


FIG. 37.

Also everything depends on properly timing the rectilinear movements. In order to describe a circle, x starts from rest when y is at the middle of its swing. This is the essential condition; and it is worth notice that if the board with a circular groove be replaced by another having a straight line groove inclined at 45° to O x, the two balls will start together from rest, and after preserving identical movements throughout will come to rest at the same instant, the difference between the times of starting giving a circle in one case and a straight line in the other.

ANALYSIS OF CIRCULAR MOTION.

70. To express analytically the relation between the movements of the points N and P we proceed as follows:—

Let $AN = x$, $NP = y$, $OP = a$, $PON = \theta$,

then $AN = OA - ON = a - a\cos\theta$,

or $x = a(1 - \cos\theta) \quad . \; . \; . \; (1)$

whence the position of N is known from that of P.

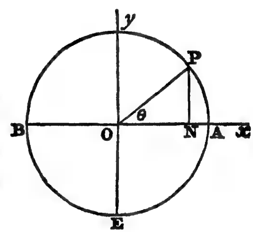


FIG. 38.

In comparing the velocities of the same points it is usual to refer to the calculus and differentiate, when we have:—

$$\frac{dx}{dt} = a\sin\theta \times \frac{d\theta}{dt},$$

and remembering that velocity of N $= \frac{dx}{dt}$, and velocity of P $= a\,\frac{d\theta}{dt}$, it is apparent that

$$\frac{\text{vel. of N}}{\text{vel. of P}} = \sin\theta \quad . \; . \; . \; (2)$$

Equations (1) and (2) contain the whole theory of the subject, the first defining the law according to which the point N travels along A B, and the second indicating the velocity with which it moves at any instant. That velocity being variable, its value may be most readily assigned by a process in the differential

calculus, but it may also be deduced by geometrical reasoning, and the student would probably be able to solve the problem for himself, now that the answer has been given.

THE MOTION OF AN INDICATOR PENCIL.

71. The model serves extremely well to exhibit the combination of movements which occur in tracing an indicator diagram.

For this purpose replace the board with a circular groove by another having an indicator diagram traced upon it. As the pin P travels round the outline of the diagram it is apparent that the index y will rise or fall with the fluctuations of the steam pressure, while the ball x moves to and fro horizontally with a motion derived from that of the piston of the engine, though on a diminished scale. Watt's first idea was to observe only the motion of y, but the invention was completed by combining therewith the reciprocation derived from the piston. The model presents an image of this combination of motions in a manner which renders it perfectly intelligible.

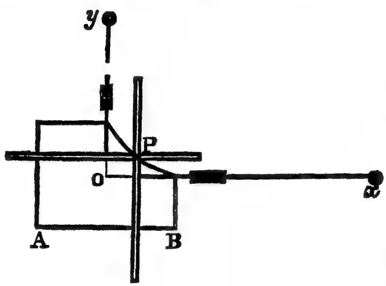


FIG. 39.

THE SUN AND PLANET WHEELS.

72. The *sun and planet* wheels, as used in the early rotative steam engines, were invented by Watt, and were employed for converting the reciprocating motion of the working beam of an engine into the circular motion of the fly-wheel. They involve a distinct principle in mechanism, which is applied in the construction of some governors of steam engines.

In a note upon this invention Watt says :—'Having made my reciprocating engines very regular in their movements, I considered how to produce rotative motions from them in the best manner; and, amidst various schemes which were subjected to trial or which passed through my mind, none appeared so likely

to answer the purpose as the application of the crank in the manner of the common turning lathe.' He goes on to say:—'I proceeded to make a model of my method, which answered my expectations; but having neglected to take out a patent, the invention was communicated by a workman employed to make the model to some of the people about Mr. Wasbrough's engine, and a patent was taken out by them for the application of the crank to steam engines. In these circumstances I thought it better to endeavour to accomplish the same end by other means. Accordingly, in 1781 I invented and took out a patent for several methods of producing rotative motions from reciprocating ones, amongst which was the method of sun and planet wheels.'

It appears that in 1780 a patent (No. 1,263) was granted to J. Pickard, of Birmingham, for a 'new invented method of applying steam engines to the turning of wheels.' In the specification it is stated that a lever, commonly called a crank, is fixed to the shaft or arbor of a great wheel, the pin of the crank being inserted into one end of a spear or carrier, the other end of which spear is connected by a moving joint with the regulating or great working beam, and in some cases to the piston, of the fire engine cylinder. This is precisely the mode of connection now ordinarily adopted.

The drawing shows Watt's invention as specified in a patent of 1781 (No. 1,306). C B is the working beam, and A B is the spear or connecting rod; E is a wheel fixed upon the end of the shaft or axis F, which receives the rotatory motion which is communicated to it by a second wheel, firmly fixed to A B in such a manner that it cannot rotate. Behind E B there is a heavy wheel, G G, having a groove or circular channel around its circumference, into which a pin at the back of A enters. The wheels A and E are thus kept in gear, and some such precaution is indispensable, but instead of the wheel with the groove and pin there may be a link connecting A and F. The construction having been described, the specification states that in the working of the engine the connecting rod pulls the wheel A up and down; and since its teeth are locked in the wheel E and it cannot turn upon its own axis, it cannot rise or fall without causing E to turn upon the axis F. When the two wheels A and E have equal numbers of teeth the

wheel E makes *two* revolutions on its axis for each stroke of the engine.

In proving this result we shall assume that an imaginary *arm* connects the centres of the wheels A and E.

Let E make x revolutions in one double stroke of the piston; then the arm makes one revolution in the same time, and the wheel A remains practically at rest. Therefore E makes $x-1$ revolutions relatively to the arm, while A makes $0-1$ relatively to the same

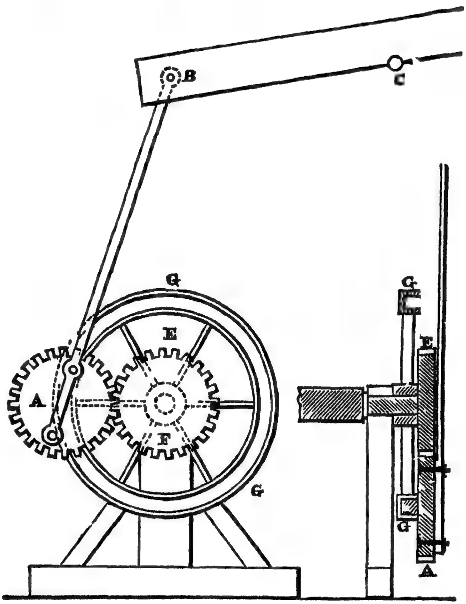


FIG. 40.

arm; also E and A are two equal wheels in gear, and consequently their relative rotations are equal in amount and opposite in sign. It follows that

$$-1 = \frac{0-1}{x-1} \therefore x-1 = 1, \text{ or } x = 2.$$

That is, the wheel E makes two revolutions while the wheel A is carried once round it.

After explaining the contrivance Watt makes one most important observation :—'And in order that the motion may be more regular I fix to or upon the shaft or axis F, or to or upon some other wheel or shaft to which it gives motion, a *heavy wheel or flyer*, to receive or continue the motion communicated to it by the primary movement.' And further, that in the cases to which this method may be applied, 'a flyer or heavy rotative motion should be applied in order to equalise the motion.'

The heavy wheel or flyer is the *fly-wheel* which gives smoothness and regularity to the motion of the shafting employed for driving the machinery of mills.

THE CRANK AND CONNECTING ROD.

73. We pass on to analyse the conversion of circular into reciprocating motion by means of a *crank and connecting rod.*

A crank being a lever or bar movable about a centre at one end, the connecting rod may be a bar attached to a sliding piece moving between guides, as in an ordinary direct acting engine.

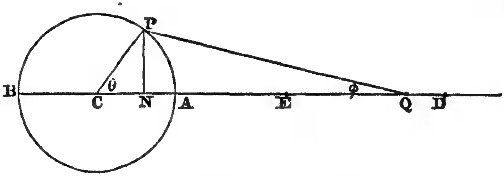


FIG. 41.

Let C P represent an arm or crank centred at C, and attached by means of the connecting rod P Q with a point Q constrained to move in the straight line C D.

Draw P N $\perp^r$ to C Q, and let C P $= a$, P Q $= b$, P C A $= \theta$, P Q A $= \phi$.

$$\text{Then } CQ = CN + NQ$$

$$= a\cos\theta + b\cos\phi.$$

$$\text{But } \frac{\sin\phi}{\sin\theta} = \frac{a}{b} \therefore \sin\phi = \frac{a}{b}\sin\theta,$$

$$\text{whence } \cos\phi = \sqrt{1 - \frac{a^2}{b^2}.\sin^2\theta},$$

$$\therefore \text{CQ} = a \cos\theta + \sqrt{b^2 - a^2 \sin^2\theta},$$

which gives the relative positions of Q and P at any instant.

Cor. 1. Let $\theta = 0 \therefore \text{CD} = a + b$,

$$\theta = \pi \therefore \text{CE} = -a + b,$$

whence $\text{DE} = \text{CD} - \text{CE} = 2a$.

The length DE is called the throw of the crank.

Cor. 2. If we refer the motion of Q to the point D we have

$$\text{DQ} = \text{CD} - \text{CQ} = a + b - a\cos\theta - b\cos\phi,$$

or $\text{DQ} = a(1 - \cos\theta) + b(1 - \cos\phi)$.

This result might have been predicted beforehand, for it is evident that the circular motion of P round the fixed point C carries Q through a space $a(1 - \cos\theta)$, and that in the same time P is describing a circular path round the moving point Q, whereby, after completing the arc $b\phi$, it superadds the space $b(1 - \cos\phi)$. In other words, the circular motion of P round C gives rise to the ordinary reciprocating motion represented by $a(1 - \cos\theta)$, while, at the same time, the swinging of PQ through an angle ϕ superadds an inequality represented by $b(1 - \cos\phi)$.

Cor. 3. As b becomes more nearly equal to a the inequality will rise in importance, and the particular case where b is equal to a should be noticed. In that case $\phi = \theta \therefore \text{DQ} = 2a(1 - \cos\theta)$.

$$\text{Let } \theta = \frac{\pi}{2} \therefore \cos\theta = 0, \text{ and DQ} = 2a.$$

The conclusion is that the inequality becomes so great that the motion fails. The point Q would move up to C when the crank had revolved through 90°, and CP and PQ would then rotate round C as one piece, the movement of Q along DC having come to an end.

Cor. 4. The relative velocities of P and Q should be investigated, because a comparison of their values at any instant will afford a comparison also of the pressures doing work at these respective points.

Let $\text{DQ} = x$, then $x = a + b - a\cos\theta - b\cos\phi$,

$$\therefore \frac{dx}{dt} = a\sin\theta\,\frac{d\theta}{dt} + b\sin\phi\,\frac{d\phi}{dt}.$$

$$\text{But } \frac{\sin \phi}{\sin \theta} = \frac{a}{b},$$

$$\therefore b \cos \phi \frac{d\phi}{dt} = a \cos \theta . \frac{d\theta}{dt}$$

$$\therefore \frac{dx}{dt} = \left\{ a \sin \theta + a \sin \phi \frac{\cos \theta}{\cos \phi} \right\} . \frac{d\theta}{dt}$$

$$= \frac{a \sin (\theta + \phi)}{\cos \phi} . \frac{d\theta}{dt}.$$

$$\text{or } \frac{\text{vel. of Q}}{\text{vel. of P}} = \frac{\sin (\theta + \phi)}{\cos \phi}.$$

WATT'S PARALLEL MOTION.

74. Hitherto we have described the piston and pump rods of an engine as being suspended by chains from the great working beam, a state of things which might have been tolerable in a single acting engine, but which was an absolute bar to the application of this type of engine for driving machinery. The idea of the necessity of a beam as part of a steam engine having apparently been adopted by the first makers of engines, it was, as Mr. Bramwell has pointed out, extremely difficult to persuade them to get rid of this particular construction and to set to work on any other method.

And indeed one of Watt's first inventions in mechanism, and probably that which he regarded with more satisfaction than any other, was a combination of linkwork for enabling the piston to act 'both by pushing and by drawing,' as he expressed it, on the working beam or great lever of an engine. The contrivance is described in the specification of a patent of 1784 (No. 1,432) to J. Watt, for 'improvements in steam engines.' The patentee states :— 'My second new improvement on the steam engines consists in methods of directing the piston rods, the pump rods, and other parts of these engines, so as to move in perpendicular or other straight or right lines without using the great chains and arches commonly fixed to the working beams of the engines for that purpose, and so as to enable the engine to act on the working beams or great levers, both by pushing and by drawing, or both, in the ascent and descent of their pistons. I execute this on three principles. . . . The third principle, upon which I derive a perpendicular or

right-lined motion from a circular or angular motion, consists in forming certain combinations of levers moving upon centres, wherein the deviation from straight lines of the moving end of some of these levers is compensated by similar deviations, but in opposite directions, of one end of other levers.'

The annexed sketch is taken from the original drawing deposited in the Patent Office.

A B is the working beam of the engine, the piston rod or air-pump rod being jointed at P to the rod B D, one end of which is attached to an iron bar, C D, centred on a fixed support at C.

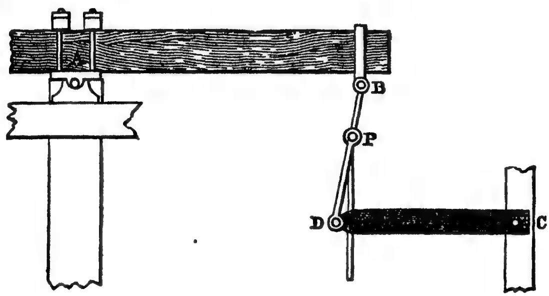


FIG. 42.

As the beam oscillates the point B describes a circular arc on the centre A, and the point D describes a like arc on the centre C, 'and the convexities of these arcs, lying in opposite directions, compensate for each other's variation from a straight line, so that the point P, at the top of the piston rod, which lies between these convexities, ascends or descends in a perpendicular or straight line.' This is Watt's account of the invention, and for full details we refer the student to practical treatises. At present it may suffice to discuss one or two geometrical propositions which place it in a clearer light.

75. In order to simplify matters we will examine the case where A B = C D.

Taking A and C as the centres of motion, and B D the connecting link, we observe that B describes a circular arc with its convexity turned to the right, and in like manner D describes an identical circular arc with its convexity turned to the left.

Some point in B D will describe a straight line, and our object is to find its position. Now B D manifestly begins to shift in the direction of its length, and hence the required line will coincide with the normal position of B D. It is also evident that the point P, which most nearly describes a straight line, must bisect B D; for the end B is describing a circle round A, and the end D is describing a circle round C, and it is only at the centre of B D that the tendency to describe a curve with a convexity approaching that of the path of B is or can be neutralised by the tendency to describe another curve with an equal convexity in the opposite direction, due to its connection with the arm C D.

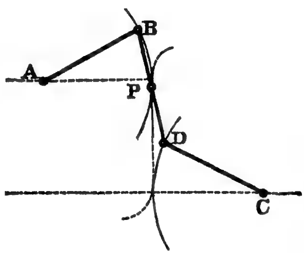


FIG. 43.

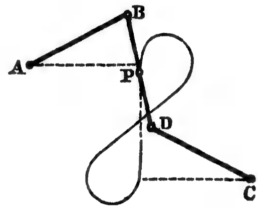


FIG. 44.

The defect of the contrivance is, that when the motion is pushed to an extreme degree, so that the connecting link tends to come into a line with either arm, the point P deviates sensibly into a curved path. By carrying B D round as far as it will go we obtain the figure in the sketch, which is made up of two intersecting straight lines (or lines not sensibly deviating therefrom) running into curved loops.

In truth, this is not *exact* straight line motion at all, and the path of P, even where it is apparently most accurate, only approximates to ideal excellence. But it is sufficiently near the truth for all practical purposes, and there appears no indication of any better or simpler combination for producing the same result. An exact straight line motion has, indeed, been discovered, and will be discussed presently, but it requires *seven* bars instead of three only for producing the motion in its most simple and elementary form.

In practice the beam of an engine seldom swings through an angle of more than 20° on each side of the horizontal line, and within that limit the deviation of the so-called parallel point P from a true rectilinear path is quite inconsiderable, as may readily be shown by analysis or verified by construction. Before entering upon a technical demonstration it may be useful to refer the student to fig. 45, which is intended to confirm the correctness of the previous reasoning, by showing the manner in which the first regular looped diagram is distorted and affected by placing the pencil at the point P unduly near to the extremity D. The influence of the curvature which attaches to the path of D is now quite apparent, and a like distortion in the opposite direction would occur if the describing point were carried towards B.

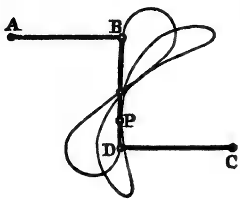


FIG. 45.

76. In like manner, if A B and C D are unequal, A B being greater than C D, the path of the point P will, if in the centre of B D, be unduly affected by the increased convexity due to its connection with the shorter arm; and in order to escape from this effect it will be necessary to move P away from D, and to bring it nearer to A B.

It is pretty clear, since we are dealing with circular arcs, that the point P must now approach B in a proportion identical with that given by comparing A B with C D, or that we should have

$$\frac{b\,\mathrm{P}}{d\,\mathrm{P}} = \frac{\mathrm{CD}}{\mathrm{AB}} \text{ as in fig. 46.}$$

It is easy to construct models and to verify the principle of Watt's parallel motion, when it will be found that the point P must be kept away from the shorter arm.

The analytical proof is the following :—

Refer now to fig. 46, and suppose the rods to be moved from the position A B D C into another position, A b d C. Draw $b\,m$, $d\,n$ perpendicular to A B, C D, respectively, and let P-be the point in B D which most nearly describes a straight line.

Let $AB = r$, $bP = x$, $BAb = \theta$.
$CD = s$, $Pd = y$, $DCd = \phi$.

We shall suppose in what follows that the motion of AB and CD is restricted within narrow limits, and shall deal approximately with our equations by substituting for the sine of an angle the corresponding value of its circular measure :—

$$\text{Then } \frac{x}{y} = \frac{bP}{dP} = \frac{Bm}{Dn}$$
$$= \frac{r(1 - \cos\theta)}{s(1 - \cos\phi)}$$
$$= \frac{r}{s} \times \frac{2\sin^2\frac{\theta}{2}}{2\sin^2\frac{\phi}{2}}$$
$$= \frac{r\theta^2}{s\varphi^2} \text{ nearly}$$

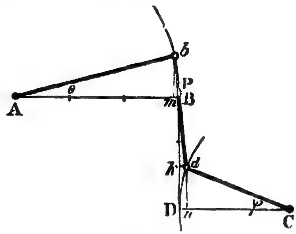


FIG. 46.

But the link itself begins to move in the direction of its length, whereby, as a first approximation, its angular motion may be disregarded, in which case $bm = dn$, or $r\theta = s\varphi$ nearly.

$$\therefore \frac{x}{y} = \frac{r}{s} \times \frac{s^2}{r^2} = \frac{s}{r}$$

$$\text{or } \frac{bP}{Pd} = \frac{CD}{AB}$$

that is, the point P divides BD into two parts, which are inversely as the lengths of the nearest radius rods.

Cor. 1. If AB and CD are so placed that their centres both lie on the same side of B, it will be found that P lies in BD produced, but we shall still have $BP : DP :: CD : AB$.

Cor. 2. If it be desired to calculate the amount of deviation of the path of P from the normal direction of DB we shall confine the investigation to the case where $AB = CD$.

Let DB move into the position bd by shifting vertically and rotating through an angle α.

$$\text{Then deviation of P} = \frac{dk - Bm}{2}$$
$$= \frac{r}{2}(\cos\theta - \cos\phi) \quad . \; . \; . \quad (1)$$

$$\text{Also let } BD = l, \text{ then } l + mb = l\cos\alpha + an$$

$$\text{or } l + r\sin\theta = l\cos\alpha + r\sin\phi$$

$$\therefore r\sin\phi = r\sin\theta + l(1 - \cos\alpha) \quad . \quad . \quad . \quad (2)$$

$$\begin{aligned} \text{Again,} \quad l\alpha &= Bm + Dn \text{ very nearly} \\ &= r(1 - \cos\theta) + r(1 - \cos\phi) \\ &= 2r(1 - \cos\theta) \text{ nearly.} \end{aligned}$$

$$\therefore \alpha = \frac{2r}{l}(1 - \cos\theta).$$

By substituting this value of α in equation (2) we can deduce ϕ with considerable accuracy, and calculate the required deviation of P.

$$\text{Ex.—Let } \theta = \frac{\pi}{9}, \text{ and assume } r = s = 50 \text{ in., } l = 30 \text{ in.}$$

$$\therefore \alpha = \tfrac{10}{3}(\cdot 0603074) = \cdot 2010247.$$

Or α represents an angle of $11° 31'$.

$$\begin{aligned} \therefore \sin\phi &= \sin 20 + \tfrac{3}{5}(1 - \cos 11° 31') \\ &= \cdot 3420201 + \tfrac{3}{5}(\cdot 0201333) \\ &= \cdot 3541001. \end{aligned}$$

$\therefore \phi$ represents an angle of $20° 44'$ nearly.

$$\begin{aligned} \text{Hence deviation of P} &= \tfrac{50}{2}(\cos 20 - \cos 20° 44') \\ &= 25(\cdot 0044544) \\ &= \tfrac{1}{10} \text{ inch approximately.} \end{aligned}$$

It may be shown that this amount of deviation is again capable of reduction, if we cause the centres of motion, A and C, to approach each other by shifting them horizontally through small spaces, the angles ABD and CDB being thus rendered each a little less than a right angle. This is a well-known artifice.

SCOTT RUSSELL'S STRAIGHT LINE MOTION.

77. Another straight line motion has been suggested by Mr. Scott Russell as applicable in the conversion of reciprocating into circular motion in the case of steam engines. We propose to discuss it, not on account of its utility, for there would probably be some difficulty in finding an example in a working engine, but because it forms a step in the progressive stages which carry us to the complete solution of the problem of drawing a straight line.

Some very useful combinations in mechanism may be derived from propositions in Euclid by simply arranging a diagram model with movable joints.

For example, the angle in a semicircle is a right angle. Taking this proposition, let B A D be a right angle, B D a rod forming the diameter of a circle B A D whose centre is C, and jointed to A by a link A C.

If the end B be constrained to move in the horizontal line A E the point D will traverse the vertical line A F, in virtue of the property that the angle in a semicircle is a right angle.

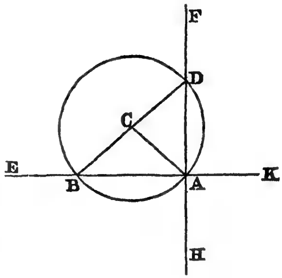


FIG. 47.

In this way a straight line motion is obtained, but it is not exact, being simply a copy of the truth of the line A E. In practice A E would be the surface of a so-called 'true plane,' upon which B would slide, and the truth of the line F D would be the same and no greater than that of the approximate plane. Mr. Scott Russell's idea was to connect the end of the piston rod with the point D, and to adapt this construction to any given engine.

78. The previous proposition has commended itself also to an inventor, J. Booth, who took out a patent in 1843 (No. 9,824) for a 'means of converting rectilinear into rotatory motion or the converse.'

Since the point A is fixed and A C remains constant, it follows that the centre, C, of the given circle will itself describe another equal circle round the point A. Whence, if F H, E K be two rectangular grooves, divided at A, and the ends of the bar B D be provided with pins running in the grooves, the rotation of C A will cause D to slide up and down in F H, while B slides to and fro along E K.

In like manner if the end of a piston rod moving in a vertical cylinder be connected with D, and there be a flywheel to carry the crank C A over the dead points, we should have a combination capable of application to a steam engine.

Recurring now to Art. 73, Cor. 3, we can extricate the movement from the failure there pointed out, and shall obtain the singular result that the throw of the crank becomes doubled.

As before, let the point B move to and fro in the line E K, and instead of working with a crank A C and a connecting rod C B produce the connecting rod B C to the point D, making C D = C B. Then attach a pin at the end D and supply two vertical grooves in the line H F, leaving a break about the centre, A.

If now we rotate the crank C A round the centre of motion A, it will be found that B oscillates through a space equal to 2 B D, and that the throw of the crank is 4 A C. There is a model showing this result in the collection of apparatus belonging to the School of Mines.

GRASSHOPPER ENGINES.

79. A modified form of Mr. Scott Russell's arrangement was carried out many years ago in the marine engines of a vessel named the 'Gorgon,' and may be met with in an analogous shape in small engines, which are convenient in the workshop, and are known as '*grasshopper* engines.' The device has been to replace the slide on which B moves by a lever centred at some distance below it, whereby B describes the small arc of a circle which is approximately a straight line.

Here the point F is attached to the end of the piston rod, also

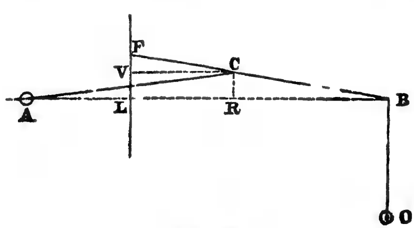


FIG. 48.

A and O are fixed centres of motion, and B is connected with O by the arm O B. We will take the case when C F and C B are unequal.

Draw C R $\perp^r$ A B and C V $\perp^r$ F L, which latter line is the direction of the piston rod.

$$\text{Let AC} = a, \text{ CB} = x, \text{ CAB} = \theta,$$
$$\text{CF} = b, \qquad \text{CBA} = \phi.$$

$$\text{Then AR} = a \cos\theta = a\left(1 - \frac{\theta^2}{2}\right) \text{ nearly,}$$

$$\text{CV} = b\cos\phi = b\left(1 - \frac{\phi^2}{2}\right) \quad ,,$$

$$\therefore \text{AL} = a - b - \frac{a\,\theta^2}{2} + \frac{b\,\phi^2}{2}$$

But A L $= a - b$, since F describes the line L F, $\therefore \dfrac{a\,\theta^2}{2} = \dfrac{b\,\phi^2}{2}$

$$\text{Also } \frac{a}{x} = \frac{\sin\phi}{\sin\theta} = \frac{\phi}{\theta} \text{ nearly,}$$

$$\therefore a \times x^2 = b\,a^2, \text{ or } x^2 = a\,b,$$

which determines the position of the point B, when the motion is correctly performed.

In a grasshopper engine B F is the working beam, and B O is a vibrating pillar at one end; the piston rod is attached at F, and the connecting rod is jointed at a point intermediate between C and B. The great advantage, besides compactness of form, is that the power and the resistance act on the same side of the fulcrum of the working beam, and that the friction thereon is correspondingly reduced. It is an objection to an ordinary beam engine that the power and the resistance act on opposite sides of the fulcrum, whereby the resultant pressure influencing friction is the sum of these forces, instead of being only their difference; or, to state the matter differently, in one case the beam is a lever of the second order in the other case it is a lever of the first order.

PEAUCELLIER'S EXACT STRAIGHT LINE MOTION.

80. The important discovery of the method of drawing a straight line by a combination of bars jointed together, and some of which are movable upon fixed centres, was first made public in the year 1864 by M. Peaucellier, an officer of Engineers in the French army.

The combination consists of seven bars, as in fig. 49, whereof $CR = CS$, C being a fixed centre of motion; $ED = \frac{1}{2} DC$, the point

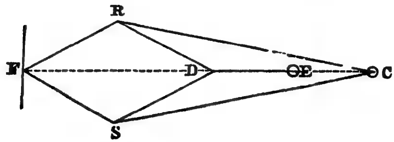


FIG. 49.

E being a fixed centre of motion; and $FR = RD = DS = SF$, the whole of the respective bars being so jointed at their ends as to permit perfect freedom of motion in the plane of the paper.

If the system be moved within the limits possible by its construction the diamond-shaped figure FRDS will open out or close up, the points R and S will describe circles about C, and the point D will describe a circle, which, if completed, would pass through the point C, but F will describe an exact straight line.

To prove this we refer to fig. 50, where the bars have been moved upwards, one half of the combination being left out for greater simplicity in the diagram.

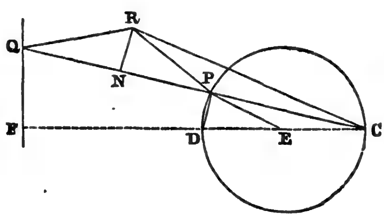


FIG. 50.

Join CP and produce it to Q, and draw RN $\perp^r$ PQ.

Let $CR = c$, $PR = b$, $PN = NQ = x$, $NR = y$.

$$\text{Then } c^2 = y^2 + (x + CP)^2$$
$$b^2 = y^2 + x^2$$
$$\therefore c^2 - b^2 = CP^2 + 2x \times CP$$
$$= CP\,(CP + 2x)$$
$$= CP \times CQ.$$

When the rods are in the normal position, as shown in fig. 49, let Q be at the point F. Join F Q and P D.

Then by parity of reasoning we have

$$CD \times CF = c^2 - b^2 = CP \times CQ.$$

$$\therefore CD : CP :: CQ : CF.$$

Hence in the triangles C Q F, C D P there is one angle common to each, viz., the angle Q C F, and the sides about this common angle are proportional; therefore the triangles are equiangular and the angle C P D = angle Q F C (Euclid, book vi. prop. 6).

But C P D is the angle in a semicircle, and is therefore a right angle; hence Q F is $\perp^r$ C F, and Q lies always in a straight line through F, which is at right angles to C F.

Hence the point Q moves in a straight line.

81. It is universally admitted among scientific men that this is a discovery of the highest value as a contribution to the science of geometry, and the student will do well to examine it carefully in detail. For this purpose he should take the combination when unfettered by the bar D E, and should establish by trial the relation between the sides, viz.:—

$$CD \times CF = CR^2 - RD^2.$$

It is usual to call the figure F R D S a *cell*, the points D and F being the *poles* of the cell, and the arm E D being introduced simply to control the motion.

Thus, if the pole D describes a circle of any given radius round some point in the direction of D C, the pole F must of necessity describe another circle whose centre lies also in the same line—it may be that these fragments of circles have their convexities in the same or in opposite directions. All that is a matter for trial or study. And again, the relative sizes of the circles will vary, so that it becomes possible to draw an arc of a circle of almost any required radius.

The case in the text is where these two circular arcs, which always co-exist when E D is centred at some point E in D C, or that line produced, are so related that the radius of one of them becomes infinite.

DUPLICATE STRAIGHT LINE MOTIONS.

82. In the application of Watt's parallel motion to the steam engine it became necessary to provide for two parallel points, as they were called, one for the attachment of the piston rod to the beam, and the other at the end of the air-pump rod.

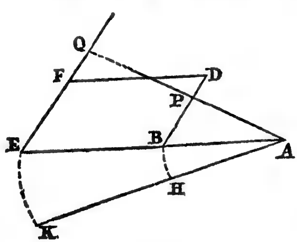
Watt solved this problem in an admirable manner by incorporating into his combination a jointed parallelogram, which gave a means of obtaining two, three, or any number of points severally describing straight lines.

In order to understand the contrivance we require in the first instance to know when two curves are similar, and in a treatise on Newton's 'Principia' the test of similarity is stated as follows:—

'Two curves are similar when there can be drawn in them two distances from two points similarly situated, such that if any two other distances be drawn equally inclined to the former the four are proportional.'

We come now to another example of the value of a movable geometrical figure.

Let B D F E be a jointed parallelogram with any given sides. Produce E F, E B to convenient lengths and take A as a fixed centre of motion. Draw any line A P Q, through A, as shown, meeting E F in Q and B D in P. It will be found that P and Q describe similar curves. This is evident, for



IG. 51.

$$AP : AQ = AB : AE,$$

and if B and E originally occupied the positions H and K we have also

$$AB : AE = AH : AK,$$

and A P, A Q both make the same angle with A K, whence P and Q always fulfil Newton's condition of similarity.

Cor. If P describes a straight line Q must do the same.

Note. The jointed parallelogram appears also as a very useful drawing instrument, called a *pantograph*, and employed for producing enlarged or reduced copies of plans or drawings. For this purpose a centre is fixed at A, and pencils are inserted at P and Q

To recur to the parallel motion of a beam engine. It is a common construction to make the arms A B, C D equal to each other, A being the centre of the working beam, and C being a fixed point for the attachment of the rod C D. In such a case the end of the air-pump rod is jointed to the middle of B D, and the parallelogram D F is added by taking B F = A B, the end of the piston rod being jointed at the angle E.

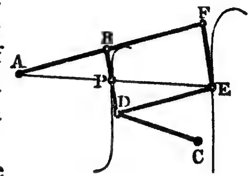


FIG. 52.

If C D be not equal to A B, it will be necessary to find B F by calculation, in order that the second parallel point may lie at the vertex, E.

Thus, let A B $= r$, C D $= s$, B F $= x$.

$$\text{Then } \frac{x}{r} = \frac{\text{D P}}{\text{P B}} = \frac{r}{s} \text{ by property of the parallel motion;}$$

$$\therefore x = \frac{r^2}{s}.$$

Hence the complete arrangement consists of two distinct portions incorporated together in the manner pointed out.

The same construction is directly applicable to Peaucellier's straight line motion.

Taking the ordinary combination, produce the lines C R, C S to the points H, L, making C H = C L, and add two bars, H T, L T, of

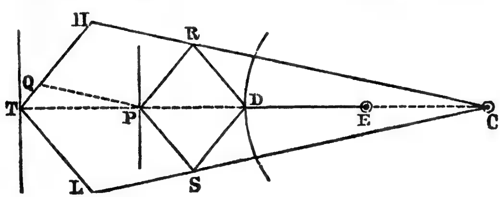


FIG. 53.

such length that they are respectively parallel to R P and S P. This parallelism must necessarily continue throughout the motion, and it follows that if P Q were drawn parallel to H R we should have an actual pantograph connecting P and T, just as Watt made it.

Hence P and T must describe similar paths, which in this case are straight lines.

For a compound cylinder beam engine, that is, an engine having two steam cylinders placed side by side under the same working beam, it is necessary to provide that three points shall respectively describe straight lines. The arrangement for effecting this object will be understood from Fig. 54.

The line A F represents one-half of the working beam, the centre of motion being at A. There is also the primary combination of two equal arms A B, C D, with the connecting link B D, and the guiding parallel point is at R, the middle point of B D.

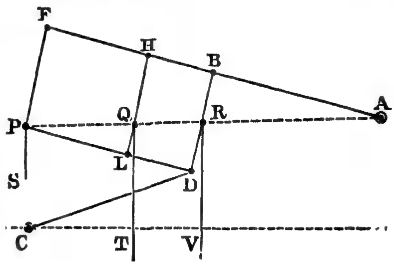


FIG. 54.

The parallelogram F B D P is the added portion, constituting the pantograph ; and the lengths of the respective lines being so chosen that A R, when produced, meets F P at the angular point P, it follows that P also describes a straight line. Also if any intermediate jointed bar, such as H L, be interposed between B and F, so as to be parallel to B D or F P, it is apparent that the point Q, where H L is intersected by A R, will fall under the same geometrical conditions as the point P, and will describe a straight line similar to the path of R.

CHAPTER V.

THE INDICATOR, AND DETAILS OF CONSTRUCTION.

83. In every branch of science our knowledge increases as the power of measurement becomes improved; and we have now to discuss, in the first instance, the measuring instrument peculiarly appropriated to the steam engine, viz., the indicator invented by Watt. The student must thoroughly understand the reading of an indicator diagram before he can appreciate the reasons for the various methods of construction adopted with reference to some of the working parts of an engine.

We begin with a few observations as to the mode of estimating work which is adopted in this country.

THE HORSE-POWER AND DUTY OF A STEAM-ENGINE.

84. Work is done by a force when some resistance is overcome, whereby the point of application of the force is continually moved, notwithstanding the resistance.

The most simple case is where the force is constant and the direction of motion is in the line of direction of the force. The work done will thus be expressed by the product of the force, or resistance, into the space described.

Definition.—The *unit of work* is the work done in lifting one pound through a height of one foot, and is called a *foot-pound.*

The number of units of work performed in a given time, say one minute, is a measure of the efficiency of the agent employed.

Watt estimated the work of a horse for one minute at 33,000 foot-pounds, and this estimate is adopted by universal consent, though it is too large. For estimating the work performed by a steam-engine the standard of measurement is technically termed a *horse-power*, and is 33,000 foot-pounds. An engine which raises

33,000 pounds through one foot in one minute is said to exert one horse-power, and its rate of doing work is determined.

When an engine is at work for a length of time it has been customary to estimate its performance by a still larger standard. Thus the term *duty* is applied to indicate the number of *millions* of pounds raised through a height of one foot by the burning of one bushel of coal.

In Cornwall a bushel of coal weighs 94 lbs., whereas in Newcastle it weighs 84 lbs. Hence, for the sake of uniformity, the measure has been altered by substituting 'one hundred and twelve pounds' for 'one bushel' of coal.

But this measure, though suitable for estimating the work done by pumping engines, is not convenient for other purposes, and it has become the practice to estimate the performance of an engine by ascertaining the number of pounds of coal burnt per hour for each horse-power at which the engine is working. This gives a useful measure in small numbers, easily remembered.

It has been a common performance with steam engines to burn 4 lbs. of coal per horse-power per hour; and in order to form an idea of the numbers which would probably be met with, we deduce the duty of such an engine as follows :—

Ex.—Let the duty be estimated by the burning of 112 lbs. of coal. Then 4 lbs. does the work represented by $60 \times 33{,}000$, or 1,980,000 foot-pounds per hour. Therefore 112 lbs. does the work represented by $1{,}980{,}000 \times 28$ foot-pounds,

$$\text{or duty of engine} = 28 \times 1{,}980{,}000 \text{ ft.-lbs.}$$
$$= 55{,}440{,}000 \text{ ft.-lbs.}$$

This being so, it follows that the duty of an engine which burns 1 lb. of coal per H.P. per hour is four times as great, or is represented by about 222 millions of foot-pounds.

85. The progress made in the economy of fuel by successive improvements in the steam engine may be readily traced by comparison of the number of pounds of coal burnt per H.P. per hour. Thus, in Smeaton's early engines on Newcomen's principle the consumption was 29·76 lbs. of coal per H.P. per hour. In his later engines it was improved to 17·6 lbs.

The reported duty of Cornish pumping engines has shown a consumption of 10·87 lbs. in the year 1811, 1·73 lbs. in 1842, and

of 2·90 lbs. in 1872. It is said that Watt began with 8·3 lbs. and went on to 2·7 lbs.

As already stated, before the year 1863 the average consumption of coal in the best marine engines was $4\frac{1}{2}$ lbs. per H.P. per hour. In the year 1872 it appeared, from a comparison of nineteen ocean steamers, that the consumption had been reduced to an average of 2·11 lbs., being a saving of 50 per cent.

Here we may notice the theoretical capability which engineers sometimes attribute to fuel. Thus, in commenting on the prevailing waste of coal, Mr. Siemens (1872) has remarked:—

'One pound of ordinary coal develops in its combustion 12,000° (Fahr.) units of heat, which, in their turn, represent $12{,}000 \times 772$ ft.-lbs. of work (9,264,000 ft.-lbs.), and these represent a consumption of barely $\frac{1}{4}$ lb. of coal per indicated horsepower per hour; whereas few engines produce an indicated horsepower with *less* than ten times that expenditure, or say $2\frac{1}{2}$ *lbs. of* coal.'

The estimate of $\frac{1}{4}$ lb. of coal per H.P. per hour may be arrived at as follows:—Since $\frac{9{,}264{,}000}{33{,}000} = 280{\cdot}7$, it appears that the performance would be to that of an engine burning 1 lb. of coal per H.P. per hour as 280·7 : 60, which is somewhat greater than 4 to 1.

We have seen in the third chapter the true meaning which is to be attached to such observations. A pound of coal can only do work by the operation of a heat engine, its function being to store up heat in a gas which does work by expanding between two given temperatures.

Let the pound of coal supply without any loss steam at 300 lbs. pressure to a perfect engine where the condenser is at a temperature of 100° F. The temperature of the steam will be 417° F.

Thus, work done $= \frac{877-560}{877}\,\mathrm{JH} = \frac{317}{877}\,\mathrm{JH} = \frac{4}{11}\,\mathrm{JH}.$

Now, JH represents $\frac{280{\cdot}7}{60}$ H.P. for 1 lb. of coal. $\frac{4}{11}$ JH represents 1·7 H.P. for 1 lb. of coal. Also $2\frac{1}{2}$ lbs. of coal for 1 H.P. is the same as 1 lb. of coal for $\frac{2}{5}$ H.P. Hence the comparison lies between 1 lb. of coal for 1·7 H.P., and 1 lb. of coal for ·4 H.P.,

which numbers are as 17 : 4, being a little more than 4 to 1, instead of 10 to 1.

In truth, we begin by throwing away $\frac{7}{11}$ of the whole heat, which passes into the condenser and is lost; and indeed we are constrained to work between temperatures which lie within moderate limits of difference, for which reason it becomes hopeless to refer to the whole heat as a standard.

IMPROVEMENTS IN THE INDICATOR.

86. The indicator, as originally constructed, was not in a form convenient for use, and it has been modified and improved by

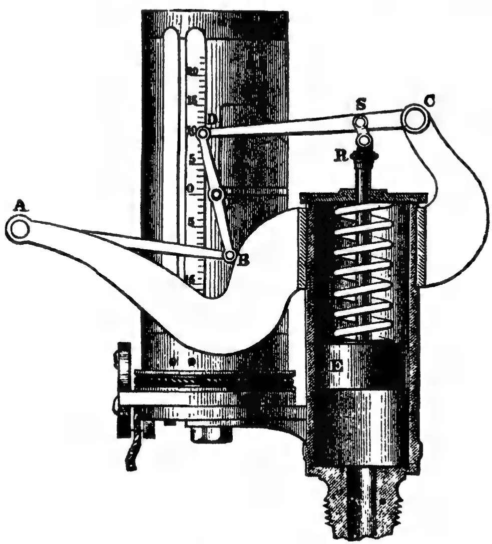


FIG. 55.

various makers. The first obvious change has been to replace the flat-board by a cylinder enclosing a spring. The cylinder is caused to reciprocate through one turn by the pull of a string attached to some piece whose motion is identical with that of the

piston, and it returns with a corresponding movement, whereby a diagram is traced upon a sheet of paper wrapped round the cylinder, just as in the former case.

Another improvement consists in reducing the motion of the piston, and magnifying that of the pencil. It is manifest that when steam at a high pressure is suddenly admitted into the cylinder of the instrument the pencil will rise with a jerk, and will oscillate with a tremulous motion during the time that it ought to be descending smoothly according to the curve of expansion. The result will be a wavy line instead of a regular curve, being the very defect which Watt said was sure to occur when the steam pressure was read by a mercurial gauge. The jumping up and down of the pencil has proved a source of great annoyance in practice, so that thoroughly good diagrams could scarcely be obtained from fast-going engines. However, Mr. Richards has overcome the difficulty by diminishing the piston-stroke and multiplying the travel of the indicator pencil, so as to bring it up to the original standard. He supplies a stronger and shorter spring than that used in an ordinary instrument, and the vibrations become inconsiderable. The drawing shows the improvement, and furnishes an illustration of a useful adaptation of Watt's parallel motion :—

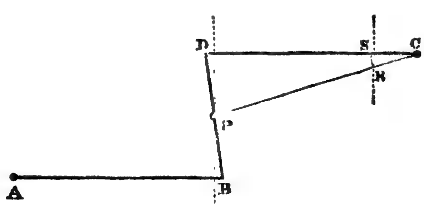


FIG. 56.

Two equal bars A B and C D are connected by a link D B carrying a pencil P at its middle point P. The piston rod E R is attached by a link R S to a point S in C D, such that C S $= \frac{1}{4}$ C D. Also when A B and C D are in the position of rest, as in the sketch, it will be found that R S is parallel to D B, and that C R P is a straight line.

It follows that, just as in the duplicate straight line motion of Peaucellier, the pantograph exists in a disguised form. Thus the

points R and P necessarily both describe straight lines, which are similar paths; and S R and D P, being parallel at starting, must remain so throughout the motion. They would be kept parallel to each other if the pantograph were constructed, and they remain parallel in virtue of the motion, which is that due to a pantograph, and not to be distinguished from it.

Hence, travel of P : travel of R = C D : C S.

In the indicator, as constructed, the movement of R is magnified about *four* times.

It should be understood that the frame carrying the parallel motion bars is attached to a collar which can be rotated on the cylinder, whereby the pencil is readily brought up to the paper or removed from it.

DIAGRAM EXHIBITING THE RELATION BETWEEN THE PRESSURE AND VOLUME OF SATURATED STEAM.

87. Hitherto we have spoken of the expansion of air either according to Boyle's law or in an adiabatic curve, but in applying the results of experiments on the expansion of steam to a practical use it becomes important to regard the behaviour of that particular substance from another point of view.

It has been shown that the pressure and temperature of saturated steam rise conjointly, though not in the same degree, and tables have been formed expressing the relation between the pressure, volume, and temperature of saturated steam. It will be borne in mind that steam in contact with the water from which it is generated is called saturated steam; and further, that when saturated steam at a high pressure expands while doing work its temperature falls, and a portion of the steam is re-converted into water. Furthermore, if we operate with saturated steam at a given temperature and endeavour to compress it, we may reduce its volume, but we cannot increase its pressure. Each temperature has its own corresponding pressure, which cannot be varied; and, as we have sufficiently shown in the first chapter, if the volume be diminished while the temperature remains constant, the only result will be that more and more of the steam will be reconverted into water, the pressure remaining unchanged.

If the relations between the pressure and volume be mapped out for any given weight of steam, we have a curve, which is of great value in interpreting the diagrams given by an indicator. It differs from Boyle's curve of expansion, it differs from the curve of expansion of superheated steam, which would be that of a perfect gas; it is a curve furnished by experimental data, and expresses the conditions which obtain when saturated steam changes its state of pressure, volume, and temperature without ceasing to be saturated.

The table generally relied on is deduced from Regnault's experiments, but as a matter of illustration we refer to the results of experiments made by Fairbairn and Tate. The substance being saturated steam, those numbers only are selected which are required for the present example :—

Pressure in lbs. per sq. inch	Temperature Fahrenheit	Specific volume
11	197·77	2167·4
12	201·96	1994·0
14·7	212	1641·5
25	240	984·8
35	259·65	713·4
36	260·83	694·5

By 'specific volume,' or, as it is sometimes termed, 'relative volume,' is meant the volume of the steam as compared with that of the water from which it is generated; and since the numbers are large it is common to reduce them by increasing the unit of volume fifty times.

Conceive now that we deal with a given weight of saturated steam at a pressure of 36 lbs. and a volume 694·5, and allow it to expand doing work. Since $3 \times 694{\cdot}5 = 2083{\cdot}5$, it is apparent that if the expansion be carried to three times the original volume the pressure will become less than 12 lbs., whereas, according to Boyle's law, it should be exactly 12 lbs. There is, therefore, a small deviation from Boyle's law in the form of the curve.

The point to be noticed is that the curve, when obtained, represents a theoretical indicator diagram. In the present example, setting out a number of intermediate points for pressures at 34,

33, &c. lbs. and registering the corresponding volumes, also calling 694·5 unity, we have the annexed diagram, where all vertical lines represent lines of pressure, and all horizontal lines refer to volumes, and where the steam is maintained in its hypothetical state by a supply of heat from without.

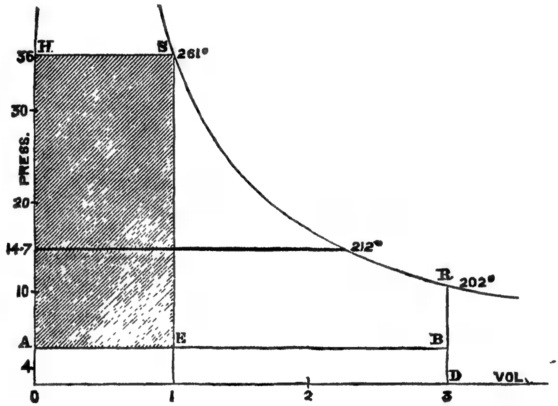


FIG. 57.

Let the horizontal line terminating at D represent the travel of the piston of an engine which is supplied with saturated steam at 36 lbs. pressure, and let the pressure be continued constant during $\frac{1}{3}$ of the stroke, as indicated by H S. The steam now expands along the curved line S R and its pressure falls to R D, which is a little under 12 lbs. A full opening is then made to the exhaust; and if the condensation of the steam were instantaneous and perfect the pressure would fall to zero, and would remain so during the return stroke. Assume that the condensation is instantaneous, but that the pressure falls only to 4 lbs., represented by B D, and remains constant till the piston reaches the end of its stroke.

The area H S R B A will represent the whole work done in the double stroke, and is contrasted with the area H S E A, which represents the work which would have been performed by the same weight of steam if there had been condensation without expansion.

In 1849 Mr. C. Cowper published a complete diagram of the expansion of saturated steam, ranging from a pressure of 2 lbs. per square inch up to 120 lbs. He stated that the diagram was 'intended to facilitate the calculation of the amount of power obtained by different methods of employing steam.' There were two divided scales, viz., (1) a vertical scale of pressures from zero up to 120 lbs. (2) a horizontal scale of volumes, giving the volume of the same weight of steam at each different pressure as compared with the water from which it was generated, one division on the scale representing 50 units of volume.

The general character of the diagram is shown in fig. 58, each little square being further subdivided into 25 squares in the published card. A dotted line represents the curve of expansion from the top of the figure according to Boyle's law. The dimensions are the following :—Line of volumes = 11 inches, line of pressures = 6 inches.

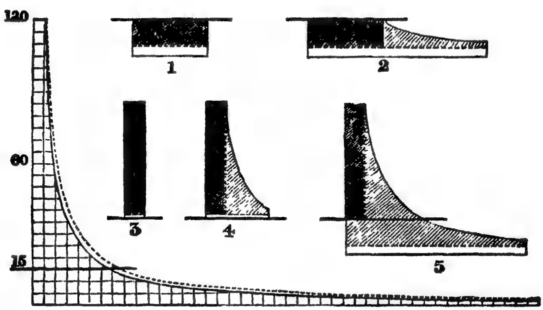


FIG. 58.

88. Having employed this expansion curve for obtaining the normal or theoretical form of an indicator diagram, which closely resembles that given by Watt, we refer to fig. 58, where five small sketches are appended, which, when rightly understood, present a summary of successive improvements in the steam-engine, the horizontal dark line being the line of atmospheric pressure throughout :—

1. The shaded rectangle is the diagram of work done by a given weight of steam when employed in a condensing engine.

The rectangle cut away at the base represents the loss by imperfect condensation.

2. The diagram of work when steam at the atmospheric pressure is expanded $2\frac{1}{2}$ times with condensation, as in Watt's early engines, before the employment of high pressure steam.

3. This figure represents the work done by an equal weight of steam at a pressure of 60 lbs., without expansion and without condensation.

4. Then comes moderate expansion of steam at 60 lbs. pressure, without condensation. It is apparent that the curve is taken in every case from the normal diagram, and here the expansion is carried to three volumes. The rectangle cut away represents, in each case, the loss by back pressure.

5. The same case repeated, except that the expansion is continued to 9 volumes, and we have the theoretical indicator diagram of an engine working according to a more economical method.

The indicator being a measuring instrument attached to the cylinder, and intended particularly to inform us as to the action of the valves connected therewith, it will be essential to give some sketch of these working parts before discussing the peculiarities of the outline traced out by the pencil.

It is not within the purpose of this book to present that full information which is to be found in large works crowded with working drawings, and it must suffice to point out enough for a fair explanation of the matter before us.

VALVE MOTION OF A SINGLE-ACTING ENGINE.—THE HYDRAULIC GOVERNOR, OR CATARACT.

89. To begin with the valve motion of a single-acting engine. It will be remembered that there are three principal valves connected with the cylinder, viz. (1) the steam valve, (2) the equilibrium valve, (3) the exhaust valve. Originally these valves were simple discs covering the respective openings, but at the present time they are balanced valves, usually of the Cornish double-beat or crown-valve construction, to be presently described. There is no rotating shaft or fly-wheel connected with a pumping engine for mines, and hence the motion available for rendering the

mechanism self-acting is not continuous but intermittent. The exact period of opening each valve will determine the number of strokes made per minute, and is the first thing to be provided for. It is evident that some independent agent must be at work to open the valves, and when that is effected the motion of the beam may be utilised for closing them at the right instant.

The independent agent referred to takes the name of a *cataract*, probably from the original form of the apparatus, which, in the early days of steam engines, was that of a vessel into which water was poured at a definite rate through a partly-opened tap. The vessel was lop-sided and tilted over, so as to discharge its contents in a sort of cataract as soon as the water had risen to a certain height. The falling over of the vessel determined the period of opening the valve with which it was connected. After a sufficient time the same valve was closed by a lever actuated by a projection or tappet on the plug rod, of which mention was made in the account of Newcomen's engine.

The principle of the cataract in its modern form will be understood from the annexed sketch. Inside a cistern partly filled with water there is placed a plunger pump P, connected with a valve O, opening upwards into the chamber of the pump, and having a tap A, capable of being regulated by a lever A *d* and a rod *d e*. The plunger P is loaded, so that after being raised it will force out water through the tap A. The valve O is fully open when the plunger rises, and closes as soon as it begins to descend, and the only escape remaining for the water is through the partly open tap, the regulation of which determines the rate at which P descends. Up to this point the cataract is a simple plunger pump, with a partly open tap in place of the usual delivery valve.

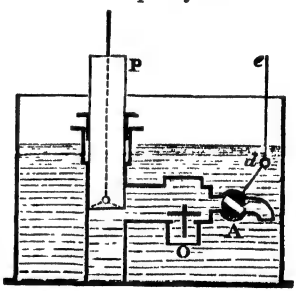


FIG. 59.

The next drawing, on p. 134, will show the external form of the cataract as well as its connection with the valves of the engine. And here we may point out that there are commonly two cataracts

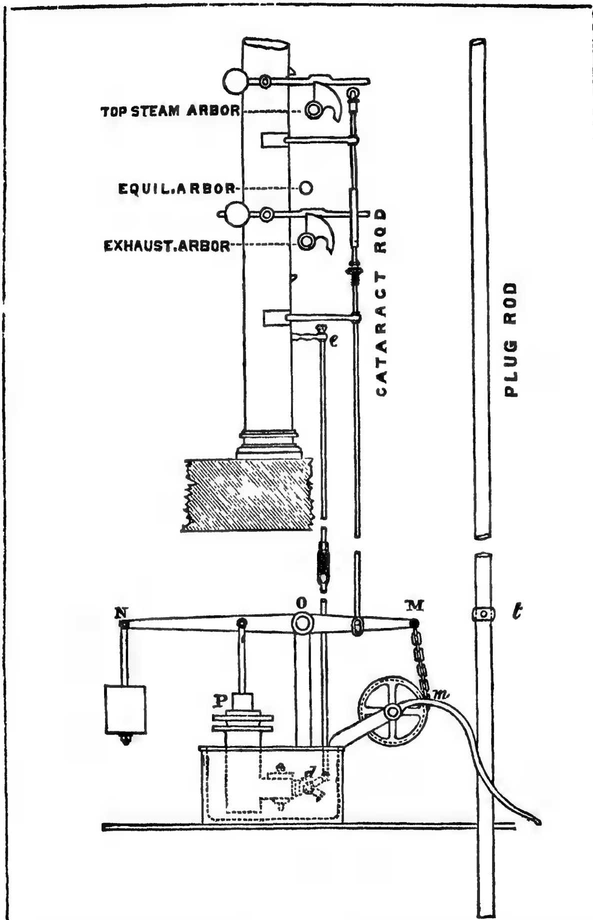


FIG. 60.

employed, the function of one being to open the steam and exhaust valves, and that of the other being to open the equilibrium valve. In the drawing the cataract is represented as acting upon the steam

and exhaust valves. The plunger P is a hollow cylinder, closed at the bottom but open at the top, and called a trunk; it is attached by a rod to the lever N O M, which is centred at O, and is raised when the tappet or projection shown at *t* on the plug rod comes in contact with the tail of the curved lever-arm springing from *m*, which lever-arm is a handle for rotating the small chain-wheel. The result is that the chain is wound up to some extent, and P is raised. The weight hung at N now causes the plunger to sink, and water is forced out at the partly open tap, the cataract rod rising until eventually its extreme end lifts the lever at the top steam arbor (that is, axis) and liberates the catch.

The regulation of the descent of the plunger being effected by opening the waste tap at *d* more or less, there is a separate bar *d e* connected with the short lever attached at *d*, which has a screwed portion, as shown, and by rotating the knob *e* at the upper end of the bar the tap may be opened or closed.

In order to complete the explanation it is necessary to turn to fig. 61, which exhibits the mechanism employed for opening and

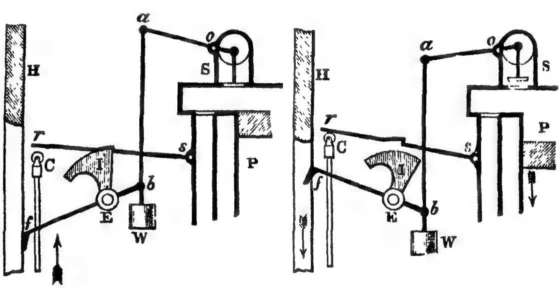


FIG. 61.

closing the steam valve S. A catch rod *r s* holds the catch I, which has a fixed centre at E. As soon as I is liberated W descends and S opens. The left-hand sketch shows the cataract rod ascending and just about to raise the end *r* of the catch rod *r s*. The tail *f* of the lever *f* E *b* will then move upward into the position shown in the second sketch, and it should be understood that the only part of the plug rod which interferes with the freedom of motion of *f* is the dark-shaded piece marked H.

When the valve S is raised the piston descends and pulls down one end of the working beam; this brings down also the plug rod, and causes the part H to strike the tail *f* of the lever *b* E *f*; and to depress it into a position ready for being locked by the catch rod *s r* as soon as that rod is set free by the sinking of the cataract rod. When once locked the valve S must remain closed until it is liberated by the cataract or by hand, for of course the valves may be worked by hand if desired. The period, or rather the portion of the length of stroke, during which the steam valve remains open is regulated by adjusting the position of the piece H, and determines the amount of expansion. In a powerful pumping engine, such as is employed at waterworks, where a weight of 30 or 40 tons is lifted some eight times in a minute, it is most remarkable to watch the steam valve lever and to note the short space of time which elapses between the opening and closing of the passage for steam.

CYLINDER, SLIDE-VALVE, AND PISTON.

90. We pass on to the cylinder, piston, and slide-valve of a locomotive engine. Several drawings would be required for exhibiting these respective parts completely, but there is not space for

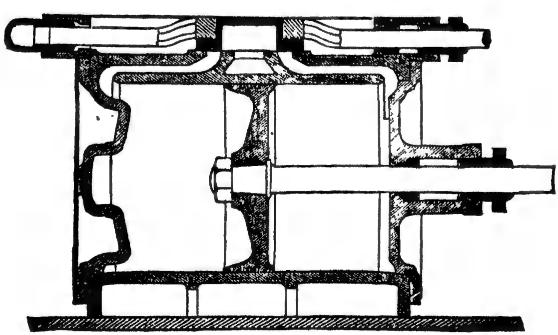


FIG. 62.

more than a longitudinal section of the cylinder, together with the piston and valve for distributing the steam.

The cylinder is 16 inches in diameter and $\frac{7}{8}$ inch thick; it is made of cast iron, and is bored out in a lathe. The thickness of a steam cylinder depends, of course, upon the diameter and the intended pressure of the steam. One cover is movable, in order to admit the piston, but the other cover is often a part of the casting. The openings into the cylinder are called steam-ports, being rectangular in shape and bounded by a plane surface scraped up so as to approximate to a so-called true plane. The ports lead into passages shown in the sketch through which the steam enters into or escapes from the cylinder.

MURDOCK'S SLIDE-VALVE.

The most important element of the combination is the slide-valve, which is in a form derived from the original invention of W. Murdock, who, in 1799, obtained a patent (No. 2,340) for an improved construction of the steam valves in Watt's double-acting engine.

91. Murdock's valve, technically called a D valve, consists of a hollow pipe A, usually semicircular in form, and attached to a rod as shown. Upon the flat side of the pipe are two plane rectangular faces which slide upon corresponding plane surfaces having rectangular openings called ports, which form passages into the cylinder and convey the steam to either side of the piston. The sliding faces are scraped so as to be as nearly as possible true planes and work upon a corresponding plane surface, the object being to render the valve steam-tight on the plane side. The valve is cylindrical at the back, and is kept steam-tight by packing at D and E. It will be understood that the sketch is a mere lecture diagram, and does not show the construction of the several parts; thus, the packing at D and E is not carried with the valve, but is pressed against it through openings in the back of the slide-case. Any steam which enters the central portion by the passage indicated will circulate freely round the pipe, while the space below the valve is permanently open to the condenser.

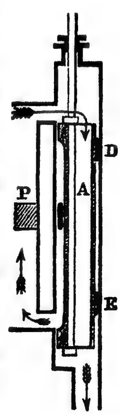


Fig. 63.

In the drawing steam is entering below the piston P, and is

driving it upwards, while the steam above P escapes through the upper port, passes down the hollow pipe, and enters the condenser. Upon raising the slide-valve the reverse takes place, for steam enters at the upper port and escapes through the lower port directly into the condenser.

Each end of the pipe may be regarded as a separate valve, and accordingly in Murdock's account of his invention it is stated that the upper and lower valves are worked by one rod or spindle, the stem or tube which connects them being hollow, 'so as to serve for an eduction pipe to the upper end of the cylinder, by which means two valves are made to answer the purpose of the four used in Mr. Watt's double engine.' It will be remembered that a diagram showing the arrangement of the four valves in Watt's early engine has been already set out at page 37.

OTHER SLIDE VALVES.

92. Another form of valve derived from the above is called a box valve, being a sort of box with plane faces and containing a passage along the back of it. Here the packing may be dispensed with, but a third port becomes necessary, so that in one sense the contrivance is less simple. It is sketched in fig. 64, where A is the upper steam port, B the lower steam port, and C the eduction port. The drawing shows steam entering above the piston at A, and escaping through B into C, and so to the condenser; whereas, by lowering the valve, steam would pass into the space below the piston at B, and would escape from the upper part of the cylinder into the passage formed by the valve, which would now lead directly into the condenser. It will be readily seen that the flat portions of the valve are in steam-tight contact with the faces on which they work.

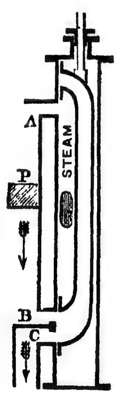


FIG. 64.

93. If the ports be interchanged, so that C lies between A and B, the construction of the valve is greatly simplified, and it is no longer necessary that it should assume the form of a pipe, for it may be a simple box with flat faces. Such a valve is applied in engines of every class, but is of universal use in locomotive

engines, and is distinguished as a locomotive D valve, or three-ported valve. It is the valve shown in the section of a cylinder and its appendages which has led to this discussion about valves, and may be conveniently studied in the following example, which is taken from an oscillating engine working in one of the boats on the Thames.

The annexed diagram shows the steam ports A and B, together with the eduction port C, and a passage S leading to the boiler. The valve and ports are covered by a rectangular box or casing, seen in section in fig. 66. The metal surface *a b c d* surrounding the ports, including the intermediate bars *m n*, is carefully planed in the first instance, and is usually scraped afterwards, according to the method originated by Sir J. Whitworth, so as to be as nearly as possible a true plane surface. In the year 1840, when slide-valves scraped up to a standard surface plate first came into use,

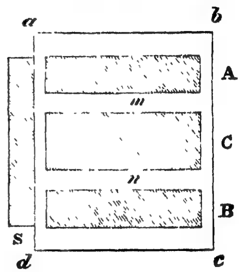


FIG. 65.

and were tried against others prepared on the old plan by grinding with emery, it was stated by the Superintendent of the Manchester and Liverpool Railway, in answer to a letter from Mr. Whitworth: 'I have this day taken out a pair of valves got up with emery that have been in constant wear five months, and I find them grooved in the usual way. The deep grooves are $\frac{1}{8}$ inch deep, and the whole surface, which is 8 inches broad, is $\frac{1}{16}$ hollow or out of truth. Those that are scraped are perfectly true, and likely to wear five months longer.'

The grooving action which here arose, probably from the emery-powder which adhered to the metal, has in some form or other always been a source of difficulty, and is also traceable to the inequality of wear due to the open faces of the ports as compared with the sides. Mr. Webb has accordingly patented a circular slide-valve which is free to rotate in the buckle that holds it; 'so that if the valve should have a tendency to seize in any one part of the sliding surface, which would put more friction on that

particular side, it will immediately begin to revolve, and so rectify itself by bringing different portions of the surfaces to bear.' The steam ports are annular segments on this construction, the exhaust port being circular. A pair of valves exhibited at a meeting of the Institution of Mechanical Engineers in 1877 had run 20,000 miles on the North-Western Railway, and the surfaces were polished by wear, but appeared to be perfectly true.

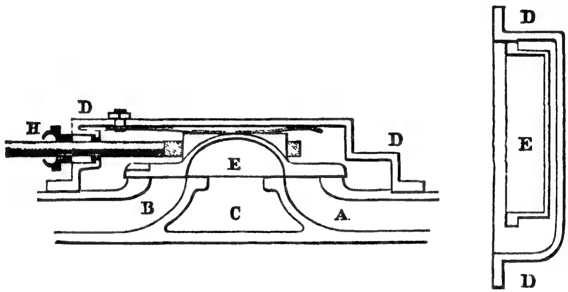


FIG. 66.

The next drawing shows (1) an outside casing D D, which forms a receiver into which the steam enters on its way from the boiler; (2) the valve E and its spindle ; (3) a stuffing-box and gland at H, forming a steam-tight collar through which the spindle passes; (4) the steam passages marked A and B respectively, and the eduction passage C which leads directly into the condenser.

Two sections are given of the valve and the slide case, one a longitudinal section through the valve spindle, the other a cross section through the middle of the slide case, showing the breadth of the valve. Taken with the plan of the ports, these sketches make the construction of the whole apparatus sufficiently clear. Also it is apparent that when the valve moves to the left sufficiently to uncover the port A, there will be an escape for steam from B into the condenser, the arch of the valve forming a passage from B to C. On moving the valve sufficiently to uncover the port B to the steam there will be an escape through A into the condenser. The action is, therefore, precisely the same as in Murdock's valve.

THE PISTON AND ITS PACKING RINGS.

94. We come now to the piston and the method of packing it so as to prevent any steam from passing from one side to the other by leakage. The drawing (fig. 62) shows the piston wrought in one solid piece, and dished out so as to form a deep surface of contact with the sides of the cylinder. Here the depth of the guiding surface of the piston is 4 inches, and the three grooves shown in section are intended for the reception of metallic packing rings, as applied by Mr. Ramsbottom about 1854, and which form the simplest method that has been devised for keeping the piston steam-tight under the high pressure employed in locomotive engines. The contrivance is thus described in a paper on an improved piston for steam-engines :—'Three separate grooves, each $\frac{1}{4}$ inch wide, $\frac{1}{4}$ inch apart, and $\frac{5}{16}$ inch deep, are turned in the circumference of the piston, and these grooves are fitted with elastic packing rings. These rings, which may be of brass, steel, or iron, are drawn of a suitable section to fit the grooves in the piston, and are bent in rollers to the proper curvature, the diameter of the circle to which they are bent being about $\frac{1}{10}$th larger than the cylinder. They are placed in the grooves in a compressed state, and along with the body of the piston are thus put into the cylinder, care being taken to block the steam-port. The rings are therefore forced outwards by their own elasticity, which is found quite sufficient to keep them steam-tight.' Of course the rings are put on so as to break joint. One object in the construction of this particular piston has been to reduce as much as possible the amount of rubbing surface. It is a maxim in books on mechanics that the amount of friction is independent of the extent of surfaces in contact, but that rule only applies where the surface is directly supporting a pressure, and it has nothing to do with the friction of a piston, where an increase of surface undoubtedly increases the friction. Here the lightness of the piston reduces the friction, and so also does the small amount of elastic surface pressed against the interior of the cylinder.

As to the amount of bearing surface, it appears that for an 18-inch piston it would come to about 42 sq. inches, whereas in a

piston of the same diameter with $2\frac{1}{2}$ inch packing rings the area of rubbing surface would be 141 sq. inches. The simplicity of construction is also an advantage, the only workmanship expended on the piston being that of turning its rim and forming its centre. The packing rings are drawn as ordinary wire, and are afterwards bent into shape, the cost of production being very small.

The mode of attaching the piston rod is apparent from the sketch. There is a shoulder, and the rod terminates in a coned end, the whole being screwed up tight by a nut. The cylinder covers are copies of the configuration of the piston, thereby avoiding a waste of steam.

PISTON OF AN OSCILLATING CYLINDER.

95. In contrast with the locomotive piston, 28 inches in diameter, take a piston for an oscillating cylinder of a large paddle-wheel steamer, the work done by which is 300 nominal H.P., but is really much greater.

In the present example the piston is made of cast iron, and is 88 inches in diameter. It has to support the enormous driving pressure of the steam, which at 13 lbs. per square inch would amount to 35 tons, and is constructed of two plates of iron of great strength, increasing from $1\frac{1}{4}$ inch in thickness near the cir-

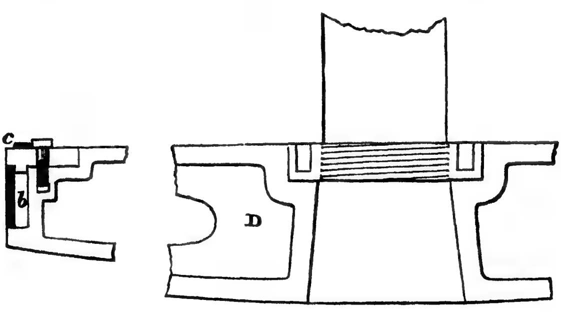


FIG. 67.

cumference to $1\frac{3}{4}$ inch near the piston rod, being further strengthened by six ribs of iron, indicated in the sketch, each of which is $1\frac{1}{2}$ inch thick. The depth of the piston is 7 inches at the

packing ring, and increases to about 13 inches near the centre, whereby every vertical radial section presents an analogy to a cantilever or beam supported at one end.

There is one large metallic packing ring, made of cast iron, 5 inches deep, and $\frac{5}{8}$ inch thick. It is turned in the lathe, and then cut through and jointed with a tongue, so as to be the exact size of the cylinder, an outward elastic pressure being maintained by junk packing, which is wound round the piston behind the ring in the empty space *b*, and is held down and compressed as well as forced outwards by a ring with a shoulder. This ring is tightened on by a series of bolts, whereof one is seen in the drawing, having square heads to prevent their becoming loose, and being retained in position by one tight encircling ring, *c*.

The piston rod is 10 inches in diameter, coned at one end, and secured by a nut 16 inches in diameter. The nut is tightened up by a long lever, which has a forked end, terminating in two pins, which enter the recesses shown in the nut.

BALANCED VALVES.

96. The next point to be considered is an improved construction of valve which will permit of an opening being made with but little effort in a space exposed to the full pressure of steam. The subject-matter for alteration is the old disc valve employed by Watt, and shown in the annexed drawing, as being lifted by a rack and segmental pinion.

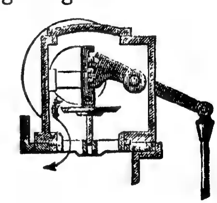


FIG. 68.

The steam pipe opens into the box or casing above the valve, and the steam therefore presses with its full force upon the surface of the disc, which cannot be raised until that force is overcome. It is, however, easy to vary the construction so as to remedy this defect, and the method adopted is to balance the fluid pressure by subjecting two equal areas to equal pressures in opposite directions. The applications of this principle are the following :—

1. *The Throttle Valve.*

This valve was introduced by Watt, and consists of a circular plate turning on a spindle which coincides with a diameter of the

plate. It is shown in section in fig. 69, the seats being indicated at *f*, *h*, and the point *o* being the axis of rotation of the valve. The pressure of the steam on one half of the valve—viz. *o b*—is, of course, balanced by that on the other half *o a*, and there is equilibrium in

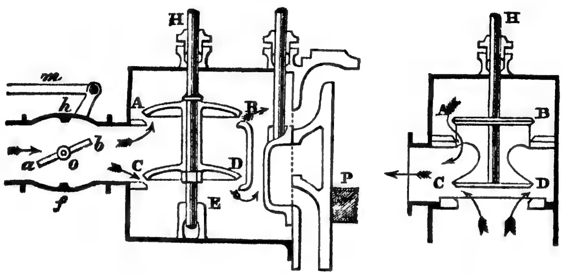


FIG. 69.

all positions. The valve is a sort of door swinging on a central line in its own plane, and is actuated by the rod *m* acting on a crank or lever handle.

2. *The Double Beat Valve.*

This valve consists of two circular discs A B and C D, threaded on the same spindle E H. The principle here relied on is again the opposition of fluid pressure on two surfaces, but the mode of application is different. Steam is supposed to be on its way to the cylinder and to have passed a regulator—viz. the throttle valve—so as to be entering the space between the discs. It is manifest that the tendency of the steam pressure is to lift A B upwards and to press C D downwards; and if the areas of the two discs be equal these opposing forces will balance, and the valve may be lifted with a very small exertion of force.

The same thing is done in organs, where it is an object to open and close passages for the supply of compressed air with comparatively little effort; but in that case the valves are discs attached to the opposite ends of a lever whose fulcrum is supported at a point raised a little above the general plane of the discs. Also the discs themselves are on opposite sides of a partition, so that one moves outwards in the direction of the air pressure, and the other inwards against that pressure, the result being the same as in the steam valve, but arrived at by a different mode of construction.

In the left-hand sketch the steam is entering between the discs, but it may come upon them from the outside, as in the adjoining diagram, and it is manifest that the principle of the opposition of fluid pressure applies equally in this case.

3. *The Cornish Double Beat or Crown Valve.*

This is a valve very extensively used, and consists of a hood or cover resting upon two seats. It matters not whether the steam passes through the valve from above downwards or in the reverse direction, and for the purpose of explanation we will assume that it is passing upwards, as shown by the arrows. The pipe H is permanently closed at the top by a fixed plate A B. The only thing movable is the part E C D, which forms a casing to the open sides of the pipe just below A B. The seats are shown in the diagram;

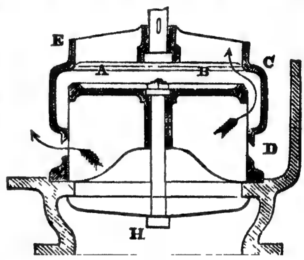


FIG. 70.

and inasmuch as the resultant vertical pressure on the inside of the curved portion C D is zero, the valve is in equilibrium when on its seat, although exposed to the full pressure of the steam. The construction of the valve is indicated in the annexed sketch, which shows an ordinary steam or eduction valve suitable for a pumping engine.

An important advantage attaches to a double-beat valve in respect of the area of opening for the passage of steam under a given amount of lift. The question is one of geometry.

Let $2r$ be the internal diameter of a pipe covered at one end by a disc of the same diameter. When the valve is raised let x be the linear motion of the disc along the axis of the pipe, and we have

$$\text{area of opening} = 2\pi r \times x.$$

But if the pipe be fully open, area of opening = area of pipe.

$$\text{Or} \quad 2\pi r x = \pi r^2.$$

$$\therefore x = \frac{r}{2} = \frac{1}{4}(2r).$$

Which proves a well-known rule, viz., that a pipe, closed by an

ordinary plate valve, is fully open when the lift of the valve is one-fourth the diameter of the pipe.

97. As a mechanical device for effecting the object in view—viz., the opening of a closed pipe against fluid pressure, with a small expenditure of force—the double-beat valve is a perfect apparatus.

An ordinary slide-valve, such as the locomotive valve, occupies a sort of intermediate position between the simple disc and the

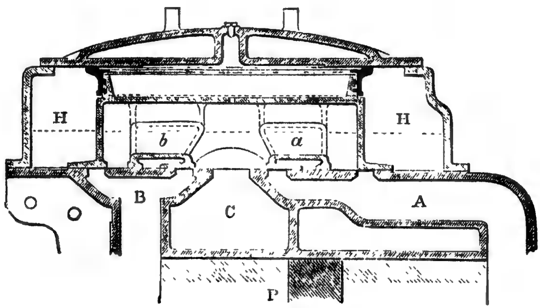


FIG. 71.

double-beat valves. It is a great deal better than one and worse than the other. If a passage be opened by the sliding of a plate over an orifice the pressure of the steam exerts no direct influence to oppose the motion, but indirectly it causes friction, which in the case of the large D valves of marine engines becomes very serious, and accordingly slide-valves are converted into so-called *balanced* valves by first boring a hole through the valve and then attaching a packing ring at the back thereof, which ring comes in close contact with the slide case and takes off the pressure from the area so encircled.

The drawing, taken from a marine engine, illustrates this arrangement. The valve and the packing ring are shown in section, and it will be noted that the back of the slide case is strengthened by arched ribs, so as to avoid any warping under pressure. The inside surface is faced, and a circular packing ring cuts off the steam pressure from the whole area which it encloses. It would be right to show this ring in plan, but there is not any great necessity for doing so, as the drawing in plan is easily supplied.

There are small packing rings, like Ramsbottom's rings in a locomotive piston, which keep the principal ring steam-tight as far as the annular portion in contact with the valve is concerned; and the upper plane surface which is in contact with the back of the slide case is pressed against it by the action of the steam on the projecting edge.

A slide-valve having been thus improved by diminishing the friction which impedes its working, the next step is to cause a

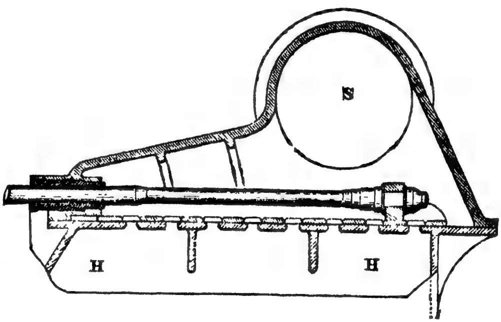


FIG. 72.

large area to be set open for the passage of steam by means of a comparatively small movement of the valve. For this purpose a distinct principle has been brought into play, which is well known in its application to the ventilators of a railway carriage, and which consists in the multiplication of a single valve several times over.

Valves of this kind are distinguished as *gridiron* valves, and there is an example in the expansion valve of the marine engine, to which the former valve belongs. Steam is admitted by the pipe S into a small chamber with a grating at the base, which is, in fact, the valve and its seat. There are eight rectangular openings for the passage of steam in the bottom of the chamber, and attached to the rod above is a plate or grating having eight corresponding rectangular slots cut in it. Supposing the valve to be so placed as just to cover all the openings, it is obvious that a motion of $\frac{1}{2}$ inch would cause each of the eight valves to open by $\frac{1}{2}$ inch, or would give the same result as with a single valve

moving through 8 half-inches. In other words, the area opened is multiplied without any increase of linear motion.

The reason for the peculiar form of the slide-valve of the engine, shown in fig 71, will now be understood. The outside shell of the valve forms an ordinary D slide-valve, but the two inner pieces, *a*, *b*, are passages through which the steam circulates. There is, therefore, a pair of steam ports communicating with the top of the cylinder, and another communicating with the bottom of it, and the length of stroke of the valve is halved with the same effective opening. This result may be of great value in powerful screw-propeller engines.

THE ECCENTRIC CIRCLE.

98. Before proceeding further it will be convenient to explain the use of an eccentric circle in actuating the slide valve of an engine. For this purpose we refer back to Art. 73, where the contrivance of the crank and connecting rod has been discussed; and, beginning with the conversion of circular into reciprocating motion in its simplest form, it will be remembered that if the connecting rod could be prolonged until it became infinite the line P Q would always remain parallel to itself, and the travel of the point Q would be represented by the equation $DQ = a\,(1 - \cos.\,\theta)$.

A crank with a connecting rod of infinite length is an imaginary creation, but there are simple combinations which will give the motion, and which have been commonly used.

1. Let a pin P, fixed in the face of a circular plate whose centre is C, move in a horizontal groove R S attached to a vertical rod passing between guides, as shown.

It has been proved that this motion causes a reciprocation in the point B, which is that of a crank with an infinite link.

2. Let a circular plate centred at C rotate in a vertical plane under a horizontal bar R S which is attached to a vertical bar E D, constrained by guides and pointing towards C, as in the previous case.

Taking P, the centre of the plate, draw P B parallel to C D, then the point of contact of R S and the plate remains in a vertical line through P during the motion. But the point P describes a

circle round C, and therefore C P is in effect a crank of fixed length; also since P B remains parallel to itself, the motion is the same as

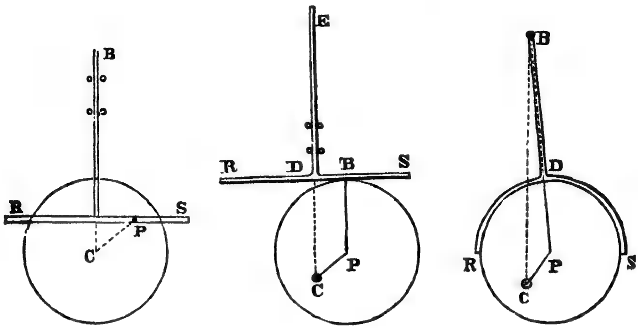


FIG. 73.

if the connecting rod between P and the piece moved by it were infinite. Thus the motion is that of a crank with an infinite link.

3. A new form, of the greatest possible utility, and giving the motion of a crank and connecting rod of any length within certain limits, is deducible at once from that last examined.

Conceive that the bar R S is wrapped round the plate so as to encircle one-half of it, and let the end B of the rod B D be constrained to move in a line pointing to C. As the circle revolves the crank C P remains constant, and the connecting rod is now P B, which may be extended at pleasure beyond the limits of the circular plate. The combination is a mechanical equivalent for the crank and connecting rod.

The form usually adopted in practice is derived from the arrangement just described. A circular plate is completely encircled by a hoop to which a bar (always pointing to the centre of the plate) is attached, the object of the complete hoop being to cause a reciprocation of B in both directions. If there were only a half-hoop, as in our sketch, the eccentric circle would drive B upwards, but it would not necessarily return, and might require the force of a spring or the action of a weight to assist in completing the double oscillation.

As before, the *throw of the eccentric* is the same as that of the

crank, viz., a space equal to the diameter of the circle whose radius is C P.

99. Having thus explained the principle of construction adopted in the eccentric, it remains to give a sketch showing the contrivance as made and applied in an engine. Usually the eccentric occupies so much space in a drawing that it is difficult to find an example suitable for insertion in the small page of this book. The annexed diagram, however, may suffice, the eccentric rod being very short, as in a small oscillating engine, from which the sketch is taken.

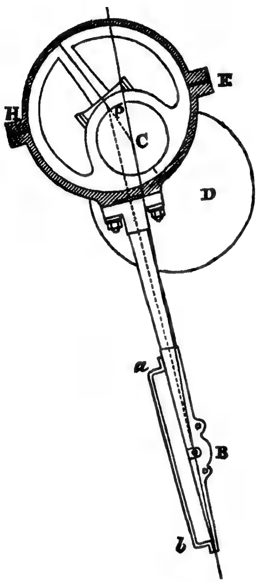


FIG. 74.

The circle C represents a section of the crank shaft, C being its centre. Upon the crank are fitted two circular half-pulleys of cast iron, which are bolted together, and have a centre at P. Two half-hoops of brass, tinted in the sketch, and united together by bolts and double nuts at E and H, carry the eccentric bar, which actuates a pin at B connected with the valve lever. The engine being designed for a river boat, and therefore requiring to be reversed at pleasure, there is a strap *a b*, to prevent the eccentric rod from falling away from the pin while the valve is being moved by hand. Also, in this case, the eccentric pulley rides loose upon the shaft within certain limits defined by stops, and there is consequently a disc D, forming a counterbalance to the weight of the pulley, which prevents it from falling out of position during the disengagement of the pin at B. It should be noted that P, the centre of the pulley, may be brought as near as we please to the centre of the shaft, and that the throw of the eccentric may be reduced accordingly; but that we are limited in the other direction, for the shaft must be kept within the boundary of the plate, and the plate itself must not be inconveniently large—considerations which are sufficient to prevent any great increase in C P.

DIRECT-ACTING ENGINE.

100. The general arrangement of a direct-acting engine in its simplest form may be made clear by the lecture diagram, fig. 75, which is taken from Dr. Anderson's collection, as published for the Science and Art Department, and represents a small vertical engine driving some light machinery.

The steam cylinder is marked C, and H is the slide case, the piston rod being connected with the crank pin by the connecting rod P R. The slide valve is worked by an eccentric, shown at E, and the eccentric rod attached to the valve spindle is marked E D.

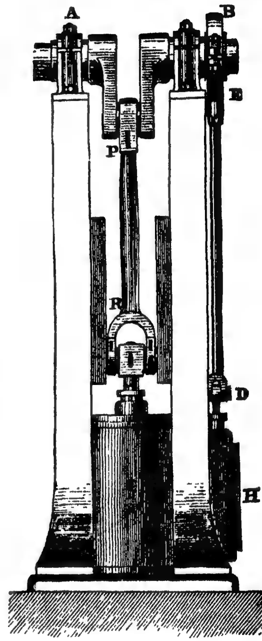


FIG. 75.

It is apparent that the use of a crank in the position shown in the drawing entails the division of the shaft A B, in order to leave an empty space which the connecting rod may sweep over. This necessarily happens unless the crank is at one end of the shaft; and the great value of the eccentric arises from the circumstance that it enables us to derive the motion which would be given by a crank and connecting rod from any part of the shaft, whether at the end or not, without forging a crank upon it or subdividing it. The main object of the sketch is to make this matter clear, and to show the conversion of the reciprocating motion of the piston into the rotation of the shafting in the first instance; and further the re-conversion of that circular motion, so set up, into the reciprocation of the slide valve. We shall presently refer to the construction of the ends of a connecting rod and the mode of fitting the brasses. As to the cranks, it is enough to say that they are frequently forged

in one solid mass upon the shaft, and are shaped afterwards by the machinery of the workshop. Where the crank shaft is of great size, as in some marine engines, a special machine tool is adapted for turning the crank pin while the shaft itself is at rest.

VALVES LIFTED BY CAMS.

101. It often happens that the steam and exhaust valves of an engine are lifted directly by *cams.* The term 'cam' is applied to a curved plate or groove which communicates motion to another piece by the action of its curved edge.

In general mechanism the particular curve which determines the nature of the movement communicated has every possible variety of form according to circumstances, but in the application of a cam-plate to the actuation of a valve all that is required is to lift the valve rapidly, then hold it raised for a certain proportion of the stroke and allow it to come down again upon its seat. It is apparent that in a simple movement of this kind, where one end of a lever is to be raised, held up, and allowed to drop, it will suffice to surround the shaft by a plate or cylinder having a circular portion *e f*, on which the end of the valve lever rests when the valve is closed, and a raised portion, A B, also circular, upon which the valve lever runs when the valve is to be opened, and which holds it open until the end of the lever runs down a slope and comes upon the lower circular portion corresponding to *e f.* For some purposes, as where steam is to be worked expansively, the raised portions are of different lengths, as A B, A C, A D, arranged in successive steps, one behind the other, whereby the valve may be held open for different periods.

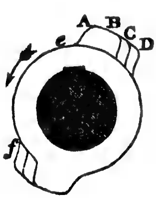


FIG. 76.

Also it is manifest that the cam may be on the face of the plate, instead of being part of its edge, and that in effect two portions of flat plates rotating about a common axis perpendicular to each, and raised one above the other, with a sloping surface connecting them, would be a mechanical equivalent for the cam described. Such a cam-plate was used by Sir W. Fairbairn.

THE LAP OF A VALVE.

102. A peculiarity in the construction of the valve described in Art. 93 could hardly escape notice, even if it were passed by without comment. Referring to fig. 66, it is seen that the arch of the valve exactly bridges over the interval between the inner edges of the steam ports A and B, but that the faces of the valve considerably overlap the ports on the outside edges. The valve is placed symmetrically with regard to the ports, and is therefore in the middle of its stroke.

In the annexed diagram there are three vertical lines intersecting a horizontal dotted line at the points O, N, and D. The space O N denotes the extent to which the face of the valve overlaps the port A, and is technically distinguished as the '*lap*' of the valve. The space N D indicates the extent to which the port A is opened for steam, and is often less than the whole breadth of the opening, the reason being that the same passage serves both for the entrance

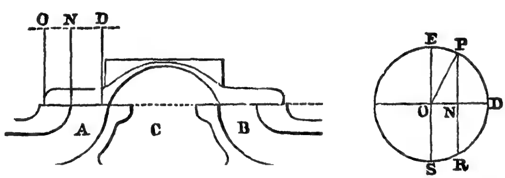


FIG. 77.

and exit of the steam, and that a larger opening is required for the rapid passage of steam into the condenser than for its admission into the cylinder.

The circle on the right hand may be taken to represent the path of the centre of the eccentric pulley which actuates the slide-valve. The diameter H D is the whole travel of the valve, and P is the point which the centre of the pulley occupies when the piston is at the end of the stroke. Draw P N R perpendicular to H D, and we have (neglecting obliquity of eccentric rod)

O N = lap of valve,
N D = opening of steam port.

Since O H represents the direction of the crank of the engine when the stroke is commencing, the first thing we observe is, that the

centre of the eccentric pulley has been set back through an angle E O P, such that O N = lap of valve, and that if there were no lap the line O P would be at right angles to O H.

The importance of putting lap upon a slide-valve will be better understood by noting what would happen without it. If there were no lap the opening for steam would be represented by O D, and the result would be that the steam port could only be perfectly closed at the precise instant when the valve was in the middle of its stroke, at which time it would be moving most rapidly. It is apparent that a valve of this kind is unsuitable for an engine, the better plan being that the steam should be compressed or cushioned on one side of the piston, so as to assist in bringing it to rest, and that the driving pressure on the opposite side should be relieved by opening a passage to the exhaust or releasing the steam, as it is termed, just before the stroke terminates. This precaution prevents the violent jerk and strain which would come upon the crank-pin if the piston were thrown with full force upon the crank at the dead points.

103. The value of an indicator diagram in interpreting the

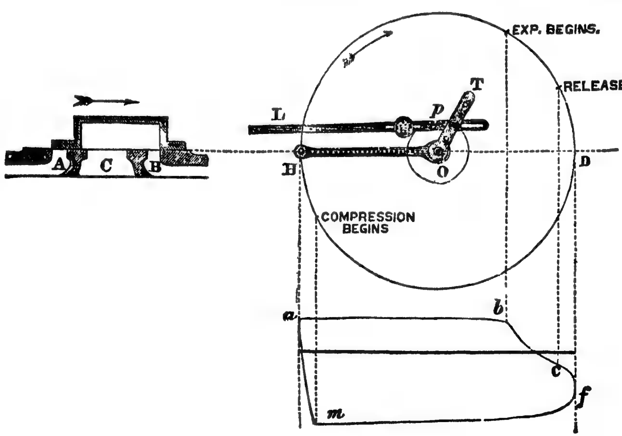


FIG. 78.

action of a slide-valve should now be made clear. The drawing will give an idea of the action of a model belonging to the School

of Mines, and intended to illustrate the relative motion of the slide-valve and piston in a direct-acting engine.

The moving parts are attached to a board carrying a sheet of paper on which the circles described by the crank-pin and centre of the eccentric are marked. Below this is a space for tracing the indicator diagram. The crank and connecting rod which actuate the piston are at the back of the board, but an index arm, O H, is placed in front and moves with the crank, thereby transferring its apparent motion to the part where it can be seen. The eccentric is represented by an actual crank, O *p*, whose extreme end describes the smaller circle, and the rod *p* L carries on the motion to the valve. The point *p* can be shifted along the arm O T, thereby varying the amount of travel of slide, and the length of the rod *p* L can also be adjusted. In this way the effect produced by any deviation from the proper length of the eccentric rod can be studied.

We are at present in a position to trace out the diagram as given by an indicator. The crank being horizontal, with the piston at the end of its stroke, the first thing to be done is to place the valve in the correct position for admitting steam by setting back O *p* until the lap is allowed for. The valve then opens; and if the pressure of the steam is sufficiently maintained, the indicator pencil will trace the horizontal line *a b*. When the crank gets to the end of the first dotted line, A is closed, so that expansion begins, the pressure falls, and we have the curve *b c*. At the point marked 'release' the valve is moved so far to the left as to open a passage from A to C, and the *release*, as it is termed, begins. The pressure falls from *c* to *f*, and continues very low till the point marked 'compression,' when B is closed, and the steam in the corresponding end of the cylinder is cushioned so as to increase its pressure, the pencil rising from *m* to *a* when the double stroke has been completed.

104. The effect of putting lap upon a slide is thus to produce a fixed amount of expansive working, and it is easy to calculate the amount of lap which should be assigned in order that the steam may be cut off at any part of the stroke.

Let the larger circle represent the motion of the crank-pin in a direct-acting engine, and let the smaller circle be the path of

the centre of the eccentric. When the crank is in the position O H, and centre of the eccentric at p, steam is just beginning to enter the cylinder. Draw $p\,n\,r$ perpendicular to O d, then r must be the centre of the eccentric when the steam is shut off, at which time let O P be the position of the crank of the engine. Draw P N perpendicular to O D.

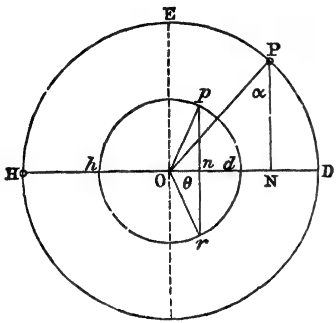


FIG. 79.

Let O P N $= \alpha$, p O $d = d$ O $r = \theta$.

Then angle H O p = angle P O r,

$$\therefore \quad 180° - \theta = \theta + 90° - \alpha,$$

$$\text{or } \theta = 45° + \frac{\alpha}{2},$$

$$\therefore \text{ H O}p = 180° - \left(45° + \frac{\alpha}{2}\right) = 135° - \frac{\alpha}{2},$$

whence the position of Op can be calculated.

Ex. Let the steam be cut off at $\frac{1}{6}$ of the stroke from the extreme end.

$$\text{Then N D} = \frac{1}{6}\text{ H D} = \frac{1}{3}\text{ O P.}$$

$$\text{or} \quad \frac{\text{O D}-\text{O N}}{\text{O P}} = \frac{1}{3},$$

$$\text{or } 1 - \sin\alpha = \frac{1}{3}, \qquad \therefore \sin\alpha = \frac{2}{3}.$$

Referring to a table of natural sines, we find that

$$\text{Sin } 41° \, 48' = \cdot 66653$$

$$\therefore \alpha = 41° \, 48' \text{ approximately}$$

$$\therefore \text{ H O}p = 135° - 20° \, 54' = 114° \, 6'.$$

$$\text{But } \frac{\text{O}n}{\text{O}p} = \cos \text{H O}p = \sin 24° \, 6',$$

and sin 24° 6′ = ·4083 by the tables,

$$\therefore \text{ O}n = \cdot 408 \times \text{O}p = \cdot 204 \times \text{travel of slide.}$$

In like manner the amounts of lap in order to cut off at dis-

tances of $\frac{1}{3}$, $\frac{1}{4}$, $\frac{1}{8}$ of the stroke from the end thereof are ·289, ·250, ·177 of the travel of valve.

105. An inspection of fig. 78 shows that the four principal points in the valve motion are (1) the admission of steam, (2) the cut-off, (3) the release or opening to the exhaust, (4) the compression or cushioning of steam behind the piston.

We have shown how to arrange for expansive working, and it remains to consider the causes which determine the periods of compression and release.

Just as expansion begins when the outside edge of the valve face comes upon the outer edge of the port A, so compression begins when the inside edge of the arch of the valve comes upon the inner edge of the port A, and it is easy to draw a figure and repeat the calculation for the compression.

When the point of compression is determined it is only necessary to cross over in a diameter of the circle to the opposite circumference, and the point of release is obtained, which is as far from D as the point of compression is from H. Thus a first general idea of the motion is arrived at.

106. Before going further two points may be noticed :—

1. A single indicator diagram does not give an accurate measure of the work done, for the line *a b c f* records the steam pressure at one end of the cylinder, and the line *f m a* records the amount of condensation and compression at the same end, but does not combine the steam pressure above the piston with the vacuum pressure below it, or conversely. In order to effect this object, which is what is really wanted, two diagrams are required, which should be taken consecutively (usually on the same piece of paper) at the top and bottom of the cylinder. An inspection and measurement of the pair of cards will give a complete opportunity of estimating the work done. It is common, however, to regard a single diagram as indicating sufficiently the general character of the performance of the engine.

2. The measurement of pressures is made from the atmospheric line, taken before steam is admitted into the cylinder of the indicator, and not from the zero line of pressures, as in the case of the theoretical diagram. This is simply a matter of convenience as it is perfectly evident that if the point *m*, for example, is at a

perpendicular depth below the atmospheric line which would give a reading of 11 lbs. on the indicator spring, that informs us that the zero line is $14 \cdot 7 - 11$ below the point m, and that the back pressure is 3·7 lbs.; and it is, in fact, easier to look only to the number 11, and not to go through a process of subtraction, in order to arrive at the same result. Of course, in any case, subtraction will be necessary when two bounding lines of the curve pass along upon the same side of the atmospheric line.

The average pressure of the atmosphere is taken to be:

14·7	lbs. per sq. inch.
2116·4	lbs. „ sq. foot.
29·922	inches of mercury.

THE LEAD OF A VALVE.

107. In a previous article we have spoken of the indicator pencil as being carried up to the highest point of steam pressure simply by compression, but it is obvious that such a movement would seldom occur in practice unless assisted from without.

Accordingly, it is the rule to open the steam port, so as to admit fresh steam into the space where the cushioning is going on, just before the piston comes to the end of the cylinder. In such a case the valve is said to anticipate or *lead* the motion of the piston; and the 'lead of a valve' may be defined as the width of opening of the steam port when the piston is at the end of its stroke.

By giving lead to a valve a strong pressure is brought against the piston just as it is reaching the end of its motion in one direction, and the strain upon the crank-pin is correspondingly relieved. The more rapid the motion of the piston the greater the necessity for giving lead, and accordingly we find that the lead in a locomotive engine is very considerable. Thus Mr. Clark, in his book on locomotives, gives $4\frac{1}{2}$ inches as the travel of a Stephenson's slide-valve, the *outside* lead being $\frac{5}{16}$ inch.

The lead of which mention has been made is outside lead; that is, it relates to the admission of steam; but of course lead can be given on the exhaust side of the valve, and in that case it would be called *inside* lead. In the case of Stephenson's valve the inside lead amounts to $1\frac{5}{16}$ inches.

DIAGRAM OF WORK DONE IN ROTATING THE CRANK.

108. The indicator gives a measure of the mean effective pressure on the piston during a stroke; and, supposing that pressure to be known, there yet remains the problem of investigating its transmission to the crank shaft. It is common to set out a diagram of work done in rotating the crank shaft, and to trace thereby the fluctuations of driving pressure as due to the position of the crank and the obliquity of the connecting rod. Such a diagram may be viewed under different conditions. First, the pressure on the piston may be taken as constant; that is, as having its mean value throughout a stroke, in which case the diagram of work done upon the crank is symmetrical, or nearly so. But, secondly, there is another way of looking at the question which is more complete and accurate, and that is, to trace the outline of the diagram of work on the supposition that the actual pressure of the steam on the piston is transmitted at each point of the diagram. This second method involves accurate drawing and measurement, and the student can easily set out such a diagram after comprehending the principle on which it is constructed.

To begin with an old proposition in applied mechanics which may be solved analytically as an exercise.

109. PROP.—To find the work done upon the crank in a direct-acting engine, friction being neglected.

Here a force P, which we assume to be constant, pulls the end D of the connecting rod D B, and turns the crank C B. Except at the dead points the line D B is inclined to D P, and it may be said that there is a force Q pulling against P in the line D B. This force

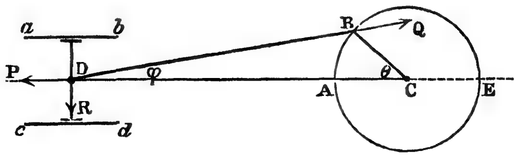


FIG. 80.

produces a reaction R perpendicular to one of the guides (friction being neglected), and R itself may be resolved into components,

one in B D, and the other perpendicular to it, whereof the former acts against Q. Hence, if B D C $= \phi$, B C D $= \theta$, we have

$$Q = P \cos \phi + R \sin \phi,$$

$$\text{also} \quad P \sin \phi = R \cos \phi,$$

$$\therefore Q = P \left\{ \cos \phi + \frac{\sin^2 \phi}{\cos \phi} \right\} = \frac{P}{\cos \phi}.$$

This result may be obtained more easily, but with less appreciation of the precise action which takes place, by resolving Q in directions parallel and perpendicular to D R, when

$$Q \cos \phi = P,$$

$$\text{or } Q = \frac{P}{\cos \phi}.$$

Let C B $= a$, D B $= b$, then moment of force to turn the crank

$$= \frac{P a \sin (\theta + \phi)}{\cos \phi}.$$

$\therefore$ work done while C B moves through an angle $d\theta$

$$= \frac{P a \sin (\theta + \phi)}{\cos \phi} d\theta,$$

$$\text{whole work} = P a \int \frac{\sin (\theta + \phi)}{\cos \phi} d\theta,$$

$$= P a \int (\sin \theta + \cos \theta \,.\, \tan \phi)\, d\theta,$$

$$\text{But } \sin \phi = \frac{a}{b} \,.\, \sin \theta \;\therefore\; \cos \phi = \sqrt{1 - \frac{a^2}{b^2} \sin^2 \theta},$$

$$\therefore \text{whole work} = P a \int \left(\sin \theta + \frac{\frac{a}{b} \sin \theta \cos \theta}{\sqrt{1 - \frac{a^2}{b^2} \sin^2 \theta}} \right) d\theta,$$

$$= P a \left(- \cos \theta - \frac{b}{a} \sqrt{1 - \frac{a^2}{b^2} \sin^2 \theta} \right) + C,$$

$$= P \times 2a,$$

the integral being taken between the limits $\theta = 0$, $\theta = \pi$.

It is well known that this result might have been arrived at directly, and without any calculation, as an application of the

principle of work. For, adopting the notation of the previous proportion, $P \times 2a$ is the work done upon the piston in one stroke, and $P \times 2a$ is also the work done upon the crank-pin in half a revolution from one dead point to the other. It may, indeed, be said that no amount of symbolical reasoning can establish the proposition more conclusively than the simple statement that it follows as a deduction from the principle of work.

110. The diagram of work done in rotating the crank, in the case where friction is entirely left out of consideration, may be set out as follows :—

1. Let the obliquity of the connecting rod B D be neglected, or let B D be supposed to remain always parallel to D C.

$$\text{Then } \phi = 0, \therefore \cos\phi = 1, \text{ and } Q = P.$$

In order to construct the diagram of work take a line equal in length to the semicircumference of the circle A C E and divide it into ten equal parts. Erect perpendiculars at the respective points of division such that each in its turn represents the resolved part of P in a direction at right angles to C B, and mark off the numbers against these perpendiculars.

For example, when B has described $\frac{1}{10}$ of the semicircumference, $P \sin\theta = P \sin 18°$, and the remaining values of θ are 36°, 54°, let $CA = 1$, and $P = 100$, and let B describe $\frac{1}{10}$, $\frac{2}{10}$ . . . of the semicircumference. Then

$$P \sin 18° = 100 \times {\cdot}3090 = 30{\cdot}90,$$

$$P \sin 36° = 100 \times {\cdot}5878 = 58{\cdot}78, \text{ and so on.}$$

In the diagram the numerical values of these magnitudes are assigned, and the curve, passing through their extremities, encloses an area which is the diagram of work done upon the crank in a semi-revolution.

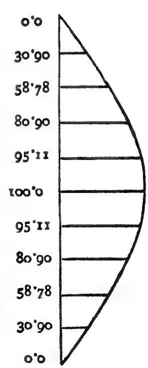


FIG. 81.

According to the proposition in Art. 109, the area of this diagram should be $P \times 2\,CA$ or 200. Now, the mean value of the ten perpendiculars, beginning at 0 and ending at 30·90, is

$$\frac{631{\cdot}38}{10} \text{ or } 63{\cdot}138.$$

Hence work done $= 63{\cdot}138 \times 3{\cdot}1416 = 198{\cdot}354$, which

approaches very closely to 200, and would be exactly 200 if arithmetical computation were capable of being extended to subdivisions as minute as those allowed for by theory.

2. Let the obliquity of the connecting rod be taken into account, and let C B $= a$, B D $= b$, as before.

We here refer to Art. 73, Cor. 4, where it is proved that

$$dx = a \sin \theta \, d\theta + a \frac{\sin \phi \cos \theta}{\cos \phi} \, d\theta.$$

$$\text{Hence } \mathrm{P}\, dx = \mathrm{P} \times a \sin \theta \, d\theta + \frac{\mathrm{P} \tan \phi}{\tan \theta} (a \sin \theta \, d\theta),$$

$$\therefore \int \mathrm{P}\, dx = a \int \mathrm{P} \sin \theta \, d\theta + a \int \frac{\mathrm{P} \tan \phi}{\tan \theta} \sin \theta \, d\theta,$$

$$\text{or work done} = \mathrm{P} \times 2a + 0 = \mathrm{P} \times 2a.$$

This mode of setting out the analysis shows that the diagram of work given, on the supposition that P remains always parallel to itself, is subject to correction when the inequality of motion caused by the connecting rod is taken into account. But the correction becomes zero in every case, for the area of the diagram of work is certainly P $\times$ 2 a, so long as P remains constant.

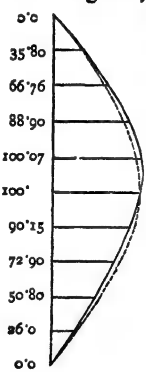


Fig. 82.

The suppositions made previously are retained in this example; that is, $a = 1$, $b = 6$, P is constant, and friction is neglected. The respective perpendiculars are varied as marked; thus 30·90 is changed to 35·80, and so on, the component of P being $\frac{\mathrm{P} \sin (\theta + \phi)}{\cos \phi}$, instead of P $\sin \theta$, as heretofore. But the variation is not large under ordinary circumstances, and the two curves are contrasted by the superposition of the dotted line which bounds the area on the first hypothesis.

Also the mean of the ten values,

0, 35·80, 66·76 . . . . 26, is 63·138, as before.

There yet remains the actual case occurring in practice where P varies at each point of the stroke, as recorded by an indicator diagram, and the effect is to slice or hollow out a large portion of

the symmetrical diagram from the point where expansion begins; and this can be done, if desired, without difficulty.

111. Connected with this subject, and forming part of it, is the estimation both of the tangential pressure upon the crank and of the thrust upon the axis of the crank shaft, friction and the inertia of the moving parts being disregarded.

Since the force Q, or $\frac{P}{\cos\phi}$, acting along the connecting rod can be resolved at once into its components,

$$\frac{P\cos(\theta+\phi)}{\cos\phi} \text{ along CB,}$$

$$\text{and } \frac{P\sin(\theta+\phi)}{\cos\phi} \text{ perpendicular to CB,}$$

we can infer the pull or push along CB at any instant of the stroke as well as the pressure acting perpendicularly to CB and tending to produce rotation. The diagram of work sets out the latter pressures, and a corresponding diagram may be constructed for the pressures in CB without difficulty.

ESTIMATE OF WORK DONE WHEN STEAM IS EXPANDED IN THE CYLINDER.

112. Having discussed the general character of an indicator diagram, as taken from a double-acting condensing engine, the next step is to estimate the area of the enclosed space.

In the case of a theoretical diagram, where the curve of expansion is that given by Watt, the true area can only be ascertained by a mathematical process. The calculation is now given, and those who are unable to follow it may take the result as established.

To find the work done in each stroke of an engine where the steam is supposed to expand according to Boyle's law:

Let CH represent the steam cylinder of an engine, PR being its piston.

Also, let $CD = l$, $CE = a$, or the space described by the piston before the steam is cut off.

$CP = x$, A = area of piston, p = pressure of steam.

$$\text{Then work done through CE} = \text{A}pa.$$

$$\text{Also pressure of steam on piston at P} = \frac{\text{A}pa}{x}$$

$$\therefore \text{ work done through space } dx = \frac{\text{A}pa}{x}dx.$$

$$\text{Whole work} = \text{A}pa\int\frac{dx}{x} \text{ from } x = a, \text{ to } x = l$$

$$= \text{A}pa \log.\frac{l}{a}$$

$$\therefore \text{ Whole work in one stroke} = \text{A}pa\left\{1 + \log.\frac{l}{a}\right\} \quad . \quad . \quad (1)$$

This is the theoretical expression for the work done by the steam on one side of the piston, and no account is taken of the back pressure from uncondensed vapour on the other side. In practice the mean back pressure should be subtracted from the mean forward pressure, viz., $\frac{pa}{l}\left(1 + \log.\frac{l}{a}\right)$, and the result will be the mean effective pressure during one stroke.

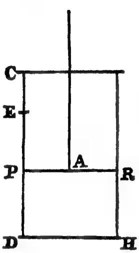


FIG. 83.

Cor. 1. To find the horse-power, or the work done on the supposition that 33,000 foot-pounds per minute is the unit of work, we multiply expression (1) by the number of strokes (say n) per minute, and divide by 33,000. Thus,

$$\text{Horse-power} = \frac{\text{A}pna\left\{1 + \log.\frac{l}{a}\right\}}{33{,}000}$$

It is a common thing to ascertain the mean pressure of the steam per stroke by measurement, much as Watt found it, and in such a case:—

$$\text{Horse-power} = \frac{\text{Area of piston in sq. inches} \times \text{mean press.} \times nl}{33{,}000}$$

Cor. 2. If $\frac{l}{a} = \text{E}$, or the steam be expanded E times, we have

$$\text{work done} = \frac{\text{A}pl}{\text{E}}\left\{1 + \log.\text{E}\right\}$$

Cor. 3. In practice there is a vacant space between the cylinder cover and piston at the beginning of the stroke, and also there is a definite space occupied by the passages leading to the valve; taking the whole content so regarded as equivalent to the volume cut off from the cylinder by a plane parallel to its base, and at a distance c from it, we have

$$\text{then work done} = \text{A}p\,a + \text{A}p\,(a+c)\int \frac{dx}{x}$$

$$= \text{A}p\left\{a + (a+c)\log.\frac{l+c}{a+c}\right\}$$

the limits being $l + c$, and $a + c$, instead of l and a.

In applying these formula it must be noted that the symbol 'log.' represents the Napierian logarithm, and not the logarithm to base 10. The two kinds of logarithms are connected by the equations

$$\text{Log. } n \text{ to base } 10 = \cdot 434294819 \times \text{Nap. log. } n,$$

$$\text{Or,} \quad \text{Nap. log. } n = 2\cdot 3025851 \times \text{log. } n \text{ to base } 10.$$

The following results for Napierian logarithms are useful :—

Log. 2 = ·6931472	Log. 5 = 1·6094379	Log. 8 = 2·0794415
Log. 3 = 1·0986123	Log. 6 = 1·7917595	Log. 9 = 2·1972246
Log. 4 = 1·3862944	Log. 7 = 1·9459101	Log. 10 = 2·3025851

113. It will be instructive to recur to the theoretical diagram set out in Art. 19, and to find its area according to Watt's method, as well as by theory.

Divide the stroke of the piston into twenty equal parts, and conceive that the steam pressure remains constant throughout each division, having (1) its value at the end of each respective division, and (2) its value at the commencement thereof. Then multiply each assumed value of the steam pressure into the distance between two consecutive divisions, and we shall obtain a series of rectangles representing work done, and lying within the curved line on one hypothesis, but overlapping it on the other. Let these be distinguished as inside and outside rectangles respectively. The pressures up to 5 are all equal, and each interval is unity, whence the pressures are as follows :—

Press. at 1 . . = 1·		Press. at 11 = $\frac{5}{11}$ = ·4545	
„ 2 . . = 1·		„ 12 = $\frac{5}{12}$ = ·4167	
„ 3 . . = 1·		„ 13 = $\frac{5}{13}$ = ·3846	
„ 4 . . = 1·		„ 14 = $\frac{5}{14}$ = ·3571	
„ 5 . . = 1·		„ 15 = $\frac{5}{15}$ = ·3333	
„ 6 = $\frac{5}{6}$ = ·8333		„ 16 = $\frac{5}{16}$ = ·3125	
„ 7 = $\frac{5}{7}$ = ·7143		„ 17 = $\frac{5}{17}$ = ·2941	
„ 8 = $\frac{5}{8}$ = ·625		„ 18 = $\frac{5}{18}$ = ·2778	
„ 9 = $\frac{5}{9}$ = ·5556		„ 19 = $\frac{5}{19}$ = ·2632	
„ 10 = $\frac{5}{10}$ = ·5		„ 20 = $\frac{5}{20}$ = ·25	

Hence area with inside rectangles = 11·572 . . (1)
Also sum of pressures from 6 to 19 = 6.322.
∴ area with outside rectangles = 12·322 . . (2)

But the true value of the area is, by the formula, 5 + 5 *log.* 4.

And log. 4 = 1·3862944 ∴ 5 log. 4 = 6·9315
whence true value of area = 11·9315 . . (3)

The mean pressure of the steam in each case is deduced by dividing these respective areas by 20.

Hence on 1st supposition, mean press. of steam = ·5786.
„ 2nd „ „ = ·6161.
„ 3rd „ „ = ·5965.

Thus Watt's estimate, the little inaccuracies in Art. 19 having been corrected, gives ·5786 as the mean value of the steam pressure, while the theoretical true value is ·5965. This shows what may be done by taking pains and subdividing sufficiently, so as to estimate by small rectangles. Watt's method is commonly followed in practice, as it is very simple and easily carried out. Further, we remark that the difference of pressure between any two consecutive divisions continually diminishes. This fact is presented to the eye by the form of the curve, which continually tends to become more nearly parallel to the line of volumes.

The differences between the pressures at 5 and 6, and 6 and 7, and so on through the series, are :—

·1667, ·119, ·089, ·0694, ·0556, ·0455, ·0378, ·0321
·0275, ·0238, ·0208, ·0184, ·0163, ·0146, ·0132.

Whereof the last difference is about $\frac{1}{12}$ of the first.

INDICATOR DIAGRAM OF ATMOSPHERIC ENGINE.

114. We pass on to discuss the performance of an engine by reference to an indicator diagram taken from it, and shall commence with an atmospheric engine. The card is taken from the collection of steam diagrams.

A scale of pressures, showing the strength of the spring of the instrument, should always be marked or recorded on the diagram, and is here noted on the vertical line at the left hand of the sketch.

Also we require to know the diameter of the cylinder, the length of stroke, and the number of strokes made per minute. The product of the number of square inches in the area of the piston and the length of stroke, when divided by 33,000, forms what may be called the *piston constant* for the engine, and the horse-power is then obtained by multiplying the piston constant by the mean pressure of the steam and the number of strokes per minute.

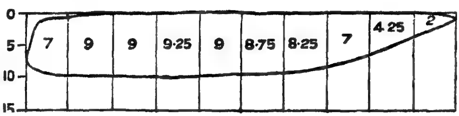


FIG. 84.

In the present example the steam pressure never rises above 0, which here marks the atmospheric line, and, as before, horizontal lines represent volumes occupied by steam in the cylinder, or otherwise the amount of travel of the piston, for one measure is identical with the other. The diagram is intersected by ten vertical lines at equal distances, dividing the length of stroke into ten equal parts, and the first thing to be done is to determine the mean pressure of the steam in each of these divisions. An estimate of this kind is to some extent uncertain, and the results are marked on the diagram, in order that the student may verify the conclusions for himself. In doing so he should remember that the outlines of the curves cannot be copied with any great accuracy, and that some corrections may appear desirable.

Referring to the diagram, the action of the steam is quite intelligible. The pressure is maintained during the upward stroke, but there is a loss at the commencement due to the injection water which remains in the cylinder. On the downward stroke the condensation is imperfect at first, but improves afterwards, and the pressure of vapour in the cylinder never falls quite so low as 5 lbs., which would be called 10 lbs. vacuum according to the usual mode of estimating it.

Adopting the numbers as printed and adding them together, we find that their sum is 73·5, which, when divided by 10, gives 7·35 as the mean effective working pressure on the piston in pounds per sq. inch during a stroke.

The dimensions of the engine and the rate at which the piston moves are now to be taken into account. In our example the diameter of the cylinder is 72 inches, the length of the stroke is 8 feet, and the number of strokes per minute is 10; hence

$$\text{Area of piston} = 4071{\cdot}5 \text{ sq. inches.}$$

$$\text{Travel of piston per minute} = 8 \times 10 \text{ feet.}$$

$$\text{Indicated horse-power} = \frac{7{\cdot}35 \times 4071{\cdot}5 \times 8 \times 10}{33{,}000}$$

$$= 72{\cdot}5.$$

INDICATOR DIAGRAM OF SINGLE-ACTING ENGINE.

115. In the single-acting engine two diagrams must be taken, one from the top and the other from the bottom of the cylinder. These diagrams are quite unlike in form, for the action during the down stroke is not repeated during the up stroke, as in a double-acting engine, and our first task will be to comprehend the reasons of the particular conformation observed. For this purpose reference is made to a diagram taken from a Cornish pumping engine, having a cylinder 70 inches in diameter, and making 4 strokes per minute, under a mean pressure of 15·1 lbs. per sq. inch. The figure is reduced from one on a larger scale, so that the indicator spring would extend one inch on the reduced diagram for a steam pressure of 40 lbs. per sq. inch.

One card is taken from the top and the other from the bottom of the cylinder, and each must be interpreted in its turn.

As far as the upper card is concerned that figure indicates the admission and cut-off of steam, together with the opening of the equilibrium valve, which corresponds to imperfect condensation in our normal diagram. The lower card has reference to the state of things below the piston, where the equilibrium and exhaust valves are opened consecutively.

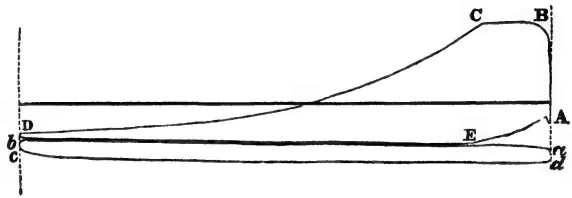


FIG. 85.

Beginning at the point A, with the piston at rest at the top of the cylinder, we note that the pressure rises until the down stroke commences when the steam line B C D is traced out. The portion B C is horizontal, and the cut off takes place at C. It is common for the steam line B C to drop considerably before the cut off begins, especially in large engines. The line D E indicates that the equilibrium valve is opened, and that the steam pressure has fallen somewhat during the circulation which takes place. At the point E the equilibrium valve is closed, and compression cr cushioning begins, just as in a double-acting engine. At the point A the piston is coming to rest, and there is a drop in the curve, which is often much more marked than in the present example and which indicates loss of pressure before the down stroke begins. Such loss would be due to leakage of the compressed steam round the circumference of the piston or perhaps to loss of heat.

As to the lower card, the nearly horizontal line *b a* shows that the equilibrium valve is opened. When compression begins at E, above the piston, expansion will also begin to much less extent below it, and there will be a slight drop towards the end of *b a*. Otherwise the lines D E and *b a* nearly coincide, and would do sc absolutely, if there were no disturbing causes at work; but the diagram shows some difference of pressure at the two ends of the cylinder when the equilibrium valve is open.

With regard to work done, the piston is driven down by the steam from above it, as opposed to the back pressure of the exhausted space underneath, and that part of the action is fully determined by comparison of the lines B C D and *d c*. But the whole work done by the steam in the double stroke is, according to our principles, obtained by a careful measurement of the areas of the enclosed figures.

At first sight the student might imagine that the horse-power may be calculated by simply noting the pressures indicated by the steam and exhaust lines, the cutting away of any part of the intermediate area—as by compression, or by want of coincidence of the lines D E and *b a*—affecting only the up stroke when the weight of the pump rods is the moving force. But a little consideration will show that such a notion is erroneous, and that the compression of steam in the up stroke and the resistance to the motion of the piston due to inequality of pressure when the equilibrium valve is open must be deducted from the total efficiency. The steam opposes the piston in its ascent to some degree, and this gives rise to negative work, which must be deducted from the positive work accomplished in the down stroke. In other words, during the down stroke the steam does the work, and during the up stroke work is done upon the steam.

It follows, therefore, that the portion of unoccupied space between the two intermediate horizontal lines is a veritable sub traction from the efficiency of the agent.

116. We pass on to calculate the horse-power in the case of

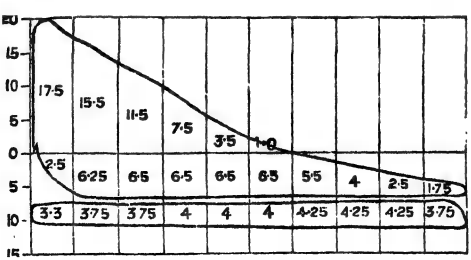


FIG. 86.

a single-acting pumping engine, having a cylinder 112 inches in

diameter, with a stroke 9·166 feet, and making 7·5 strokes per minute.

Referring to the diagram where the steam pressures are noted, and taking each group of numbers in order, there is, above the atmospheric line, a series amounting in all to 56·5. Below the atmospheric line the first series amounts to 48·5, and the second series gives 39·3.

Hence mean pressure of steam $= \frac{1}{10}(56{\cdot}5 + 48{\cdot}5 + 39{\cdot}3) = 14{\cdot}43$

$$\therefore \text{H.P.} = \frac{14{\cdot}43 \times 3{\cdot}14159 \times 56 \times 56 \times 9{\cdot}166 \times 7{\cdot}5}{33{,}000}$$

$$= 296{\cdot}5.$$

In an example of this kind the answer is very readily obtained by the use of a table of logarithms.

DOUBLE-ACTING ENGINE.

117. In illustration of the mode of estimating the work done by a double-acting engine we go back some thirty years to an example from a powerful oscillating cylinder of a marine engine, which may give an idea of the performance commonly accepted before the days of compound cylinder engines with high pressure and expansion.

The engine was composed of two cylinders, each $82\frac{1}{2}$ inches in diameter, with a stroke of 6 feet, making $14\frac{1}{2}$ revolutions per

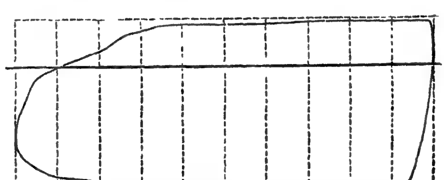


FIG. 87.

minute. It would be described as a pair of 250's, meaning that each cylinder was of 250 H.P., according to a nominal scale then adopted, but now almost, if not quite, obsolete.

The scale is not marked on the diagram, but the student will infer it approximately from the values of the steam pressures

above the atmospheric line at the respective divisions, which are

4·5, 4·5, 4·45, 4·35, 4·3, 4·3, 4·1, 2·7, ·6,

stopping at the ninth division.

The so-called vacuum pressures are estimated as follows:—

8·8, 10·8, 11·2, 11·3, 11·3, 11·4, 11·4, 11·4, 11·5, 10.

Hence the sum of pressures = 109·1 + 33·8 = 142·9;

mean pressure = 14·29.

It is recorded on the card that the steam was blowing off, and that the barometer gauge of the condenser stood at 26½.

WIRE-DRAWING AND CLEARANCE.

118. Among the causes which deteriorate from the perfection of an indicator diagram one is that of wire-drawing. This term is intended to convey the idea that the pressure of the steam is attenuated by obstacles which impede its passage.

The effect of wire-drawing is to cause a gradual decline or subsidence of the steam line. It is commonly seen in the indicator diagram of a large Cornish pumping engine. The cubic content to be filled by the steam increases so rapidly as the piston descends that the steam pressure can hardly be maintained.

Again, it will have been noticed that the definite well-marked angle at the point where the curve of expansion leaves the horizontal line of steam pressure is seldom to be noticed in an actual diagram, or certainly not in an engine worked by a slide-valve and eccentric. In such a case the valve closes gradually, and the outline becomes rounded at the point of cut-off.

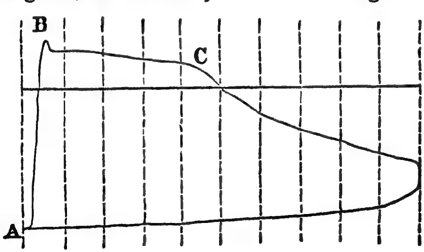


FIG. 88.

This rounding at the point where expansion begins is also marked in diagrams where the valves are lifted by cams, as in the annexed figure, which is taken from an engine by Fairbairn & Sons, having the following particulars:—

Diameter of cylinder	. . . .	40 inches.
Length of stroke	. . . . .	6 feet.
Number of revolutions	. . . .	25 per minute.

Steam is admitted a little after the crank-pin has passed the dead centre, and is cut off at ·45 of the stroke. The lead of the exhaust is $\frac{3}{4}$ inch. The valves are double-beat or balanced valves, and the exhaust is kept open during the whole stroke. Here, therefore, there is no compression; and to obviate the sudden strain on the crank-shaft from admitting steam while the piston is at the exact end of its stroke, the curve is cut away along the bounding vertical line, instead of before reaching it, as in the case of the locomotive engine.

The diagram tells at once what is happening by the little tail at the point A. Then comes the rise of steam pressure and a small jump of the pencil at B. There is also, to a small extent, wire-drawing, as shown by the gradual drop of the steam line between B and C; and there is a small rounding at the extreme end of the upper steam line, showing the lead of the exhaust.

According to a scale of the strength of the indicator spring the mean effective pressure on the piston is 11·5 lbs., the vacuum being 13 lbs.

119. Hitherto it has been assumed that the travel of the piston is exactly equal to the length of the cylinder, but in practice the piston does not come home to the cylinder cover at the end of a stroke, and a certain empty space or clearance is left between their respective surfaces. Also the steam passages leading from the valve to the cylinder increase this ineffective space, which must be filled with steam before any work can be done. The cubic content thus occupied, which causes waste when the steam is perfectly exhausted, but forms no part of the real working cylinder, is called the *clearance*. It may be estimated in terms of the content of the cylinder by assigning a length thereof (say c) which determines its volume. Thus, let A be the area of the piston, then $A\,c$ is the clearance. But for simplicity it is common to call (c) the 'clearance,' especially in analytical calculations of work done.

The tendency of compression or cushioning is to eliminate the waste due to clearance. The steam compressed at the end of the

stroke behaves like an elastic spring and gives out during expansion the work expended in compressing it, whereby it obviates, as far as it will go, the waste of boiler steam.

The effect of clearance on the indicator diagram is to lift the curve of expansion in some degree.

Thus, let A N be the travel of a piston, O A the clearance, where O is the real zero from which volumes are measured.

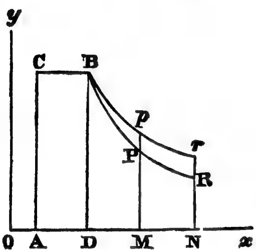


FIG. 89.

Neglecting clearance, we should assume that the volume A D expanded according to Boyle's law, and on this supposition B P R would represent the lines of pressure, whereby if A D = D M = M N we should have $\text{PM} = \frac{\text{BD}}{2}$, $\text{NR} = \frac{\text{BD}}{3}$. But since O D is the true volume of steam undergoing expansion, it is evident that tne true pressures at M and N are somewhat greater than before, and are in fact represented by p M, r N, such that

$$p\,\text{M} : r\,\text{N} : \text{BD} :: \frac{1}{\text{vol. OM}} : \frac{1}{\text{vol. ON}} : \frac{1}{\text{vol. OD}}.$$

In other words, let vol. A D = V, vol. O A = v, and let p be the pressure at B.

If there be no clearance, pressure at M $= \frac{p}{2}$

But with clearance, pressure at M $= \frac{p\,(\text{V} + v)}{2\,\text{V} + v}$

$$= \frac{p}{2}\left(\frac{1 + \frac{v}{\text{V}}}{1 + \frac{v}{2\,\text{V}}}\right)$$

$$= \frac{p}{2}\left\{1 + \frac{v}{2\,\text{V}}\right\}, \text{ neglecting } \frac{v^2}{\text{V}^2}.$$

The amount of clearance which is to be allowed for in practice may be set out upon an indicator diagram by drawing a vertical line similar to the dotted line in fig. 97, and regarding it as a zero line from which volumes are to be measured.

The indicator diagrams in fig. 90 are intended to give an idea of the effect now referred to. They are taken from a blast engine, having a cylinder 42 inches in diameter, with a stroke of 8 feet 3 inches, working at 14 strokes per minute. The smaller diagram, with the less perfect vacuum line, was taken when there was an excessive amount of clearance, the cut-off valve being placed in the steam-pipe, whereby the steam contained in a side pipe or steam-chest expanded after the valve was closed. The effect of clearance has been to raise the expansion curve in the manner pointed out in the previous investigation. That such is the case will be rendered more certain by reference to the second diagram, which is the card taken when the two valves—viz., the steam and cut-off valve—were replaced by a single valve lifted by a cam and placed close to the cylinder. The expansion curve falls at once by reason of the diminution of clearance.

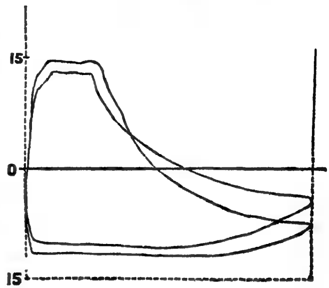


FIG. 90.

It must be noted that the pressure of the steam is not the same at the beginning of the stroke in the respective diagrams, nor is the point of cut-off exactly the same, so that the comparison is not perfect; but we see that clearance must be allowed for in estimating the expansion curve of an indicator diagram, and that otherwise the information given is entirely deceptive. Another point is, that excessive clearance diminishes the excellence of the vacuum, by reason that the condensation is less perfect when a portion of steam is lodged in the passages. This is apparent from the diagrams, the vacuum having improved from 9 lbs. in the first card to 10·9 lbs. in the second, solely from the lessening of the amount of clearance.

EXPANSIVE WORKING OF STEAM.

120. This example suggests a connection between the subject of clearance and that of expansive working as carried out by seperate

valves. It will be understood that expansion of steam may be provided for :—

1. By putting lap on a slide valve, whereby a fixed rate of expansion is secured.

2. By employing four independent valves lifted by cams, viz., two steam and two exhaust valves. Here the expansion can be regulated without any difficulty, all that is required being to change the cam-steps for different grades of expansion.

3. By employing a separate expansion valve, placed behind the ordinary slide valve.

This method will be understood by referring back to fig. 69, where a double-beat valve, acting as an expansion valve, is shown in combination with a slide valve. The latter has scarcely any lap, and contributes nothing to expansive working, its function being merely to distribute the steam on its way from the slide case to the exhaust. The double-beat valve would probably be lifted by a cam, and would regulate the passage towards the slide valve, being opened or closed at will, and at any desired period of the stroke. It does all that is required for cutting off the supply of steam, but it labours under the defect that it causes a sensible addition to the amount of clearance which is inherent to the use of a slide valve. The waste of steam now commences a step further back, and is reckoned from the valve A B C D, instead of from the slide valve. It has consequently been a common practice to retain four valves for distributing the steam in a double-acting engine, according to the method originally practised by Watt. Each of these valves may be opened and closed by cams at any period of the stroke, and they give a power of carrying out expansive working with great facility.

If, on the other hand, a combination of a slide valve with a separate expansion valve be employed, it is essential that the latter should be placed as close as possible to the former, or indeed should form part of it, as in the following instance, which illustrates an excellent mode of providing expansion, viz., by a *back cut-off* valve.

Such a valve is shown in the drawing, and is marked H.

We have here the cylinder, with its steam ports and eduction ports, as in the repeated examples. Instead of an ordinary D

slide valve there is a box with steam passages and an arch for bridging over the interval between the steam and eduction ports. It is apparent that on lowering both this box and the supplementary block behind it, marked H, the steam will enter the top of the

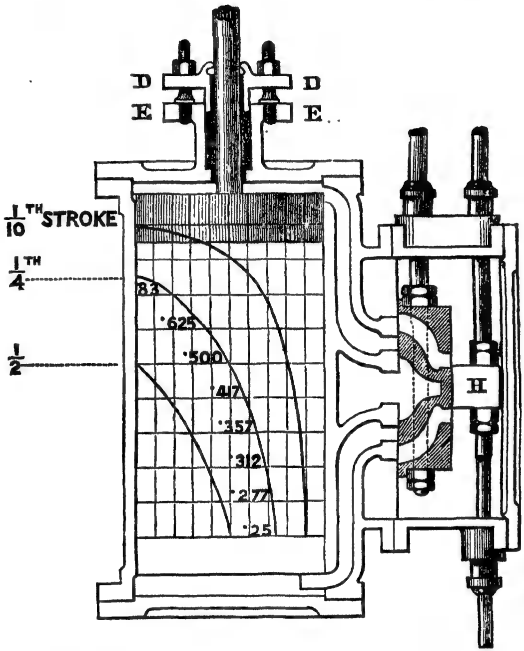


FIG. 91.

cylinder, and will escape from the bottom of it in the manner previously described. Whereas on raising the block H no more steam can enter the upper port, and an effectual cut-off is the result.

The back of the valve as well as the face of it will be plane surfaces, and, by properly adjusting two eccentrics connected with the valve and with H respectively, it is possible to provide for a cut-off at any part of the stroke, and to do so with scarcely any waste of steam other or greater than that which would occur with a single D valve.

The effect of expanding in different degrees is marked on the diagram by way of illustration, and requires no special explanation after the previous remarks, but it is necessary to notice the stuffing box and gland for keeping the piston rod steam-tight.

This is an improvement upon Watt's method, which is drawn in fig. 9, as it appeared in his patent of 1782. The stuffing box, marked E E, is provided with a brass bush at the bottom of it, which is bored to fit the piston rod. An empty space is left for packing, and a gland, D D, with a brass lining, is screwed down, so as to compress the packing and tighten it round the piston. The top of the gland is formed into a cup for oil, and this completes the arrangement.

FURTHER INDICATOR DIAGRAMS.

121. In a diagram taken from a locomotive engine the periods of expansion, compression, and release are often well marked, as confirmed by the following example, which exhibits successive

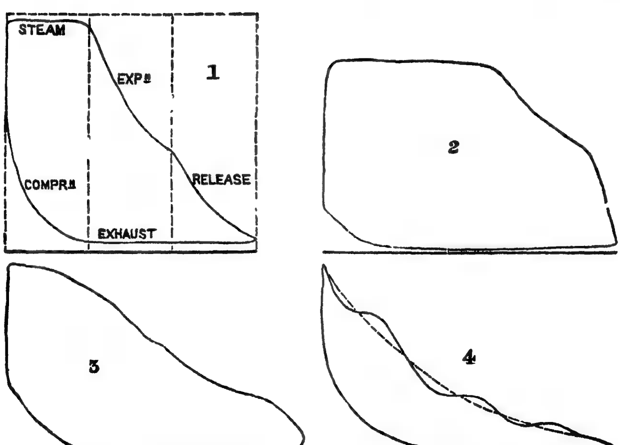


FIG. 92.

stages in the modification of the indicator figure. The engine

being non-condensing, the atmospheric line is below the whole enclosed area.

1. Here the diagram is intersected by three vertical lines at equal distances, and represents a species of theoretical curve. The steam line is maintained during the first third of the stroke; then come expansion, release, exhaust, and compression in the order and to the extent marked.

2. This is a tolerable copy of an actual diagram given to the writer, where the boiler pressure was 128 lbs., the diameter of the cylinder 17 inches, with a stroke of 2 feet. The train was described as consisting of fifteen carriages, and was just starting. The three periods in question are extremely well defined.

3. Here the three periods are still defined, but the greater speed of the engine causes them to lose much of their distinctive character. The boiler pressure is still 128 lbs., but the speed is 28 miles per hour.

4. The boiler pressure is marked at 123 lbs., but the speed of the piston has quite swept out the characteristics of the steam line. The train is now running on a level line at 58 miles per hour, and the principal effect to be seen is the jump of the indicator pencil; but, taking the dotted line as an approximate mean, it is apparent that cut-off, expansion, and release are hopelessly blended together.

122. As an illustration of the necessity of providing in the design of an engine for effective condensation of steam, we refer to a simple illustration.

Some thirty years ago, in the iron district of South Staffordshire, an indicator diagram taken from a mill engine of nearly 200

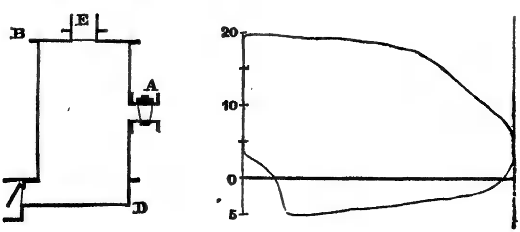


FIG. 93.

H.P., having a cylinder 42 inches in diameter, with a 7 feet stroke, gave the result shown in fig. 93. The engine took steam at about $19\frac{1}{2}$ lbs. pressure, which was maintained nearly uniform to the middle of the stroke, falling only to about $17\frac{1}{2}$ lbs., and was then reduced by wire-drawing to 6 lbs. The average vacuum was $2\frac{3}{4}$ lbs. below the atmospheric line, the lowest point attained being 5 lbs. This is made very clear by the outline of the diagram. Of course such a performance was most defective, and accordingly a careful examination was made into the construction of the engine, when it was seen that the steam and eduction valves, as well as the thoroughfares or passages, were on too small a scale. The condenser B D was of insufficient size, and water was admitted into it by a simple opening, A, without any pipe or rose for throwing out a divided stream.

The conclusion arrived at was to remodel the valves and steam thoroughfares as well as the condenser. The engine was worked by four Cornish valves, so that it was easy to supply others on a

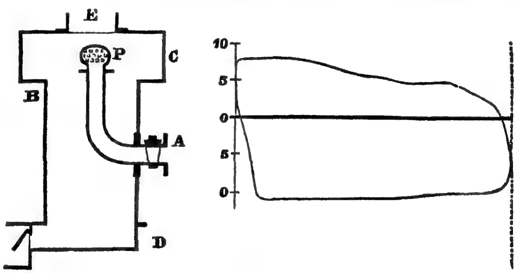


FIG. 94.

larger scale, and accordingly the steam and eduction valves were enlarged from 7 inches to 12 inches in diameter, and the pipe marked E was similarly altered. The condenser was improved by the addition of a supplemental chamber, C, and an injection pipe with a rose, P, was introduced. Otherwise the construction of the engine was undisturbed.

The altered form of the indicator diagram at once shows the gain of power. The largest portion of the area of work done is below the atmospheric line, instead of being above it, the vacuum averaging a very little over 10 lbs., instead of only $2\frac{3}{4}$ lbs. The

steam pressure commences at 8 lbs., and averages 5·4 lbs. throughout the stroke. It is instructive to note the gain of work under the new conditions, and we can form a general idea at once from the increase of effective pressure below the atmospheric line.

In the first case it was found that a mean effective pressure of 19 lbs. from steam and vacuum combined gave 190 horse-power; and in the second case there was a gain of 7·43 lbs. from condensation alone; whence it followed that the actual gain was to 190 H.P. as 7·43 to 19; that is,

$$\frac{7 \cdot 43}{19} \times 190 \text{ H.P., or } 74 \text{ H.P.}$$

123. As an additional illustration two indicator diagrams are appended, which were taken from a direct-acting horizontal engine at Woolwich. In the one diagram the engine was working much

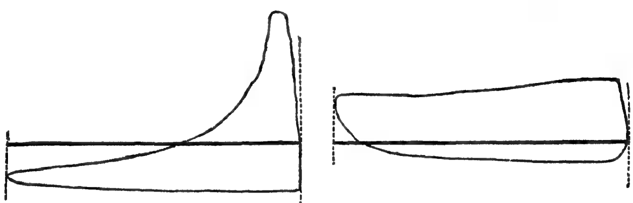


FIG. 95.

in its ordinary manner, and the curve of expansion is well marked; but in the other the condenser was leaky; and in order to keep the machinery in action it was necessary to maintain the steam pressure nearly to the end of the stroke, the contrast between the two diagrams being here greater than in the example first commented on.

PROTECTION OF THE CYLINDER.

124. There are three conditions of the steam cylinder in the working of an engine: (1) it may be entirely unprotected by any covering; (2) it may be coated with felt and wood or some non-conducting material: (3) it may be steam-jacketed, the jacket itself being covered with a non-conducting material.

1. It seems clear that the first mode of working is wrong. But in order to impress this view upon the student we refer to the annexed diagram, which shows the expansion curve of steam in an imperfectly protected cylinder, as contrasted with the true theoretical curve which would have corresponded with the weight of steam found in the cylinder at the end of the stroke. In

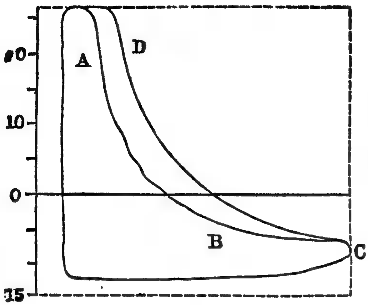


FIG. 96.

the diagram A B C represents the actual expansion curve of the steam, and D C that which should have been the expansion curve if the walls of the cylinder had detracted nothing from the work done. The steam loses pressure on its entrance by the chilling of the colder metal, and there is an immediate drain upon the molecular motion within the cylinder, on which we rely for the movement of the machinery outside. The escape of heat, from whatever cause it may arise, is a direct subtraction from the efficiency of the working substance, and at the present day it can scarcely be necessary to marshal all the reasons to be urged against such a practice.

2. The second case is where the cylinder is coated with some non-conducting material, and here it is essential to remember that steam cannot expand and do work behind a piston without a fall in temperature. If the steam enters the cylinder direct from the boiler, as is commonly the case, it will be saturated, and reduction of temperature will cause partial condensation.

As the expansion goes on it appears that the temperature of the steam will fall below that of the surface surrounding it, and towards the end of the stroke the heated metal will boil off the water deposited and send it out as steam into the condenser. By such an action steam will have passed through the cylinder without doing work. A cylinder of metal may be covered with a non-conducting casing, but it remains a large metallic mass, and it is impossible to reason about it as if it were not alternately heated and cooled during the working of the engine. It was this alternate heating

and cooling which Watt strove to eliminate by a separate condenser and a steam-jacket. In the last diagram the curve of expan sion appears to rise more than is usual towards the end of the stroke, and this indicates, as clearly as if the thing were spoken in words, that the steam which has been condensed by chilling is evaporated by the walls of the cylinder towards the close of the stroke.

Adopting a view similar to that now referred to, Mr. Cowper has pointed out that, with high expansion and a marked difference in temperature at the beginning and end of the stroke, the cylinder acts somewhat as a condenser to the entering steam, and as a boiler just before it escapes. That this is so became apparent from an experimental trial, where a glass tube closed at one end was fitted to the non-jacketed cylinder of a high-pressure engine working expansively. Mr. Cowper found that the steam condensed in a cloud inside the tube at the beginning of each stroke and re-evaporated before its conclusion. He then brought a shovel of hot coals near the tube, and the heat of the fuel effectually prevented condensation, for it acted as a steam-jacket.

The point is, that no covering to the cylinder would raise its temperature permanently to that of the entering steam, for the heat deposited on condensation would not remain, but would be carried away afterwards, during the re-evaporation.

3. The last case is that where the cylinder is covered both at its ends and sides by a steam-jacket, the external casing being also protected by a covering of non-conducting material. Under these circumstances the walls of the cylinder may be kept nearly as hot as the entering steam, and the chilling effect of the metal surface is to a great extent eliminated. Enough has been stated in the discussion on heat engines to demonstrate the serious waste of heat which is inevitable with even the best-constructed engines, and it is a clear advantage to get the greatest possible amount of work out of the steam just at the precise instant when it is in action.

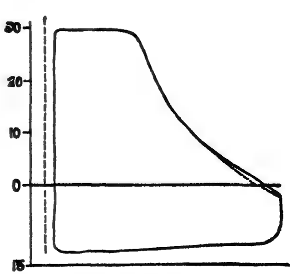


Fig. 97.

There is no known material which is insensible to the action of heat; that is, which cannot be warmed or cooled, and which will not conduct or radiate heat. Of necessity a cylinder is made of metal, a material peculiarly sensitive to changes of temperature, and possessing every quality, except strength, which we should prefer not to find in it. It would, therefore, appear that the most reasonable course would be to enclose the cylinder in a hot envelope, which may serve to maintain its temperature at a high level and to supply the heat which is otherwise escaping.

Mr. Cowper has brought before the Iron and Steel Institute several valuable observations on the utility of a steam-jacket, and he has illustrated his remarks by reference to indicator diagrams taken from cylinders with and without steam-jackets. The card (fig. 97) was from an engine with a steam-jacket over the ends and sides, and the curve of expansion was nearly that given by theory. Towards the end of the expansion the true curve is represented by the dotted line, and it appears that the actual expansion rises above it, showing that the steam was a little superheated by the hot casing. Several diagrams were adduced, which came pretty much to a repetition of that given above, the point being that the greater the amount of expansion the greater was the loss of work from the absence of a steam-jacket.

DIAGRAM FROM A CORLISS ENGINE.

125. A form of engine was introduced some thirty years ago by Mr. Corliss in the United States, and has worked successfully, although the arrangements for actuating the valves are somewhat complicated. The only point to which reference is made is the form of the indicator diagram, as taken from engines of this type.

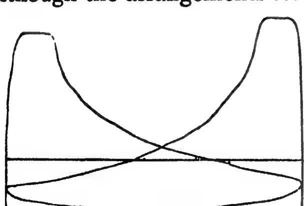


Fig. 98.

Without attempting to describe the engine, we may say that it works with two steam and two exhaust valves.

The steam valves are extremely rapid in their action; they are opened, when under the

control of springs, like the hammer of a gun, and they move suddenly into the position of being fully open. They are closed in like manner and are, as it were, shot round from the position of being fully opened to that of being fully closed, or conversely. The valves are cylindrical slides working in the arc of a circle.

It is remarkable that liberating gear for disengaging a valve which was lifted by the action of a falling weight was introduced by Watt, and is therefore as old as the condensing engine; but here the valves are not lifted, but rotated, and they are actuated by springs, and not by weights.

Another point is that in engines of this class the governor acts directly on the steam valves, so as to cut off the steam earlier, instead of actuating a throttle valve, as in Watt's arrangement.

FURTHER REMARKS ON INDICATOR DIAGRAMS.

126. It is hoped that enough has been said to present a general view of the application and use of the indicator, and before leaving this branch of our inquiries it may be useful to append a few general remarks.

Rankine, in his book on the steam-engine, discusses several causes which influence the form of the indicator diagram.

1. It appears that the steam pressure undergoes some fall during the passage from the boiler to the cylinder. The amount of such fall varies greatly in different engines, but the general result is, that the highest average indicated steam pressure before expansion begins is some two or three pounds less than the boiler pressure.

Among the points to be noticed are (1) the resistance of the steam pipe through which the steam passes, (2) the resistance of the regulator or throttle valve, (3) the resistance due to the ports and steam passages; and here also the bends or sharp angles as well as the imperfect coating of the steam pipe must be taken into account.

Rankine says that in the present state of our knowledge it is impossible to calculate separately the losses of pressure due to these causes, and if it were possible the resulting formulæ would be too complicated to be of much use. An observation of this kind has

a wide application. It may be pointed out that steam which has been lowered in pressure by the resistance of passages, or has been *wire-drawn*, as we have termed it, is to some extent *superheated* by the friction of its molecules, the tendency of all friction being to produce heat.

2. There is in practice a rounding of the angle at which the expansion curve begins in the theoretical diagram. This is called *wire-drawing at cut-off.* It is always to be seen where a slide valve, closing gradually, is employed, and is reduced to a minimum in a well-formed diagram of a Corliss engine. Speaking generally, it may be said that the steam begins, as it were, to work expansively a little before the valve is completely closed, or that the energy exerted is nearly the same as if the valve had closed instantaneously at a somewhat earlier point of the stroke, which point may be termed the 'effective cut-off.' Such a point is easily obtained by carrying the expansion curve a little higher, and by prolonging the probable steam line to meet it.

3. There is a rounding of the expansion curve when release begins before the end of the stroke, and it is recommended that the point of release should be so adjusted that one-half of the fall of pressure takes place at the end of the forward stroke, and the other half at the beginning of the return stroke. Where the release is small the expansion curve is continued to the end of the diagram, as may be seen in fig. 98, and in such a case the exhaust line slopes gradually downwards as the piston returns instead of being nearly horizontal.

4. The general effect of water in the cylinder, from whatever cause produced, but which we will suppose to be present in some degree throughout the stroke, is to lower the steam line in the first portion of the stroke and to raise it in the latter portion. On this subject it is very easy to propound theories; but the subject-matter lies so much within the region of experiment that any theoretical deductions, which are nearly all that we can be said to have at present, may indeed be interesting, but would perhaps admit of being classed among 'conclusions in which nothing is concluded.'

5. There is also the conduction of heat to or from the walls of the cylinder, the general effect of which is that in the last case.

6. Clearance will modify the form of the expansion curve of steam, by removing backwards through a small space the zero line of volumes. And, as we have seen, if the steam be completely exhausted from the cylinder during the return stroke the effect of clearance is to waste a quantity of steam during the double stroke. But, inasmuch as it is possible to compress a portion of steam in the cylinder during the return stroke, the loss above referred to may be greatly or perhaps wholly eliminated. On this subject Rankine recommends that the point of compression should be adjusted in such a manner that the quantity of steam confined or cushioned should be just sufficient to fill the clearance with steam at the initial pressure when the piston comes to rest. In such a case the work expended in compression is restored again during expansion, and the steam spring is continually reproduced without waste.

CONNECTING ROD ENDS.

127. Two principal methods of forming the ends of connecting rods will be apparent from the sketches, which are copied from the collection of lecture diagrams.

In Fig. 99 we have an elevation and side-view of a connecting-rod with a forked end, showing the combination known as a *strap*, *gib*, and *cotter*. A pin to which the rod is attached is encircled by brasses made in two halves, as indicated by the tinted pieces while the brasses themselves are bound round by the strap *c c*, and held together by the gib, marked *a*, and the cotter (sometimes called 'cutter') marked *d*. This part of the contrivance affords a good illustration of the use of

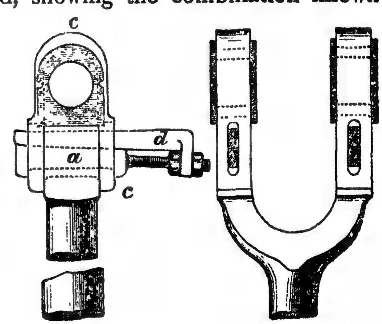


FIG. 99.

wedges in combination with a tightening screw. As the brasses wear the oblique surfaces of *a* and *d* slide upon each other, and

the thick end of the cotter is continually advanced by the screw, while the surfaces which abut against the brasses on the one side, and the connecting-rod on the other, remain parallel, as at first. The key-way, which is cut through the strap and connecting rod for the insertion of the gib and cotter, is shown in the side-view, and spaces are left to allow for the screwing up of *d* as the bearing wears. Also the connecting rod is enlarged towards the middle, as indicated by the broken piece which marks the increase in size.

128. Another construction for the end of a connecting rod is simple in its details, and is much used in marine engines, as in the compound cylinder engine by Messrs. Maudslay (see fig. 127).

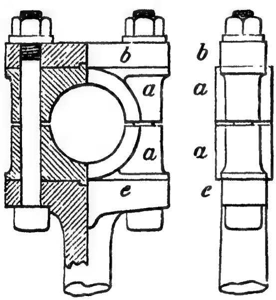


FIG. 100.

Here a brass block is divided into two parts, and is bored through for the reception of two holding bolts, each screwed at one end. The connecting rod terminates in a T-piece marked *e*, the brasses abut against it, the bolts are passed through the brasses, and a plate *b* affords an abutment to keep everything in place after the nuts have been screwed up tight and locked. A side-view shows that the central portion of the brass is elongated, in order to secure a sufficient amount of bearing surface, the advantage of elongated bearings being now well understood. The blocks may, of course, be hollowed out sufficiently to leave a layer of patent metal for diminishing the friction, the surface of the soft metal being scored by channels, so as to admit oil for lubrication. Where great force is transmitted the inside of each brass is lined with soft metal. Soft metal bearings, as they are termed, formed the subject of a patent taken out in 1843, No. 9,724. The specification stated that the inner part of the boxes for the support of gudgeons or axles was to be lined with a compound metal, composed of 50 parts of tin, 5 of antimony, and 1 of copper. In order to prepare the boxes for this composition they were 'to be cast with projecting rims or fillets along their interior edges and

on their ends, within their semicylindrical parts.' The interior of the boxes and the fillets or rims were then to be cleaned and tinned in the usual way of performing that operation. A cylindrical core was then inserted, and the alloy was melted and poured in, so as to form the lining, the object of the rims or fillets being to keep the lining in its place. The method described in the specification has been commonly adopted, and indeed the composition is so soft that it would be squeezed out unless it were retained by a harder fillet or edge. The device is an example of a means of counteracting the tendency of rubbing surfaces to set up the vibratory motion of heat. The soft plastic tin will not accept that vibration; and if the surfaces be well oiled the bearing may support great pressure without becoming heated. Where the force transmitted is very small, as in watchwork, the bearing surfaces are made of the hardest possible material; for example, a steel pivot works in a ruby collar.

Where a shaft works under water the mechanical conditions are changed, and in the case of screw-propeller shafts it has been found that hard wood bearings are superior to all others. In 1854 Mr. Penn took out a patent (No. 2,114) for 'an improvement in the bearings and bushes for the shafts of screws and submerged propellers.' According to this invention the bearings were not continuous metal surfaces, as previously constructed, but were formed in a series of wooden fillets or ridges made of lignum vitæ, and having water spaces between them, one main object being to allow the water to pass freely along the channels lying between the ridges.

CHAPTER VI.

ON BOILERS.

129. THE two forms of boilers principally used for stationary engines are the Cornish boiler and the Lancashire boiler. The Cornish boiler stands first in the history of the subject, having been adopted in Cornwall during the early part of the present century, and being, in fact, the type from which the Lancashire boiler has been derived.

The shell of a Cornish boiler is a cylinder with flat ends, having one internal furnace tube which runs along the whole length of the boiler. The furnace occupies a portion of the tube, and the burning fuel is entirely enclosed within the shell. Such a system is technically known as 'internal firing,' and if the furnace were placed outside the boiler and below the cylindrical shell, as may often be the case, the boiler would be an externally fired single-flued boiler, and the term 'Cornish' would not be applicable to it.

The Lancashire boiler is said to have been introduced in 1844 by Fairbairn and Hetherington, and is a cylindrical boiler with flat ends, having two internal tubes instead of one only, each furnace being enclosed within its respective tube.

Since there is no essential difference between these two forms of boiler, except in the number of furnace tubes, it may be convenient to describe the Lancashire boiler.

The tubes necessarily govern the diameter of the boiler; they are usually 2 feet 9 inches in diameter, and, in order to allow sufficient space between their sides and the shell, the latter should be 7 feet in diameter. With tubes 3 feet in diameter the shell would be increased to 7 feet 6 inches in diameter. The length of the boiler may, of course, be varied. Short boilers evaporate more

rapidly in proportion than long boilers, and suffer less from straining action. The maximum length is 30 feet, and the usual length for a full-sized boiler is 27 feet.

The construction of a boiler should be regarded from two points of view: (1) There is the general form and structure adapted to support the bursting pressure of the steam. (2) There are considerations arising from the unequal action of the heat of burning gases, and there are precautions to be taken for diminishing the waste of heat.

CONSIDERATIONS WHICH INFLUENCE THE FORMS OF BOILERS.

130. The early boilers were designed in simple defiance of all mechanical principles. This matter has been touched upon in Chapter III., where the opinion of an engineer was quoted, to the effect that a marine boiler should be adapted to the shape of the vessel, and that its safety would depend upon the strength of the metal, and not on its form. Without doubt the safety of a boiler depends on the strength of the metal, but it is quite wrong to say that it is independent of the form of the shell, and anyone who thinks for a moment on the subject will comprehend that a cylindrical tube of some kind is the proper vessel wherein to retain a supply of steam under pressure.

The strongest form of vessel for holding a gas under pressure is a sphere—that is the natural form for the purpose—as we learn in blowing a soap-bubble. But no one would recommend a spherical boiler, there are so many practical reasons against it.

The next best theoretical form is a cylinder, which may be of any size, and only suffers from weakness at the two ends. Accordingly, when a chemist wishes to operate on gases under enormous pressure he confines them in tubes; if he is about to expose water to a temperature which shall cause the whole of it to pass into steam approaching the density of the liquid, he encloses a small quantity in a tube. Faraday's first experiments on the liquefaction of carbonic acid gas were performed with the aid of small tubes. Cagniard de Latour found that water enclosed in a tube became gaseous in a space equal to four times its original bulk at a temperature of about 773° F. (that of melting zinc).

The practice of an engineer in this question of form has been

precisely the same as that mentioned above. When steam was first used at or about the atmospheric pressure the shape of the boiler somewhat resembled that of a teakettle. Then followed the waggon boiler of Watt, designed solely for economising heat, and shown in section side by side in contrast with a cylindrical boiler having two internal flues. In the ordinary waggon boiler the fireplace is underneath the shell, and there is an arched base for preventing an accumulation of deposit, together with curved sides for exposing a larger amount of surface in the flues. These boilers were of considerable size, and the example taken is that of a 16 H.P. boiler, which would be 11 feet 9 inches long, and 5 feet in breadth. It would contain 238 cubic feet of water, and

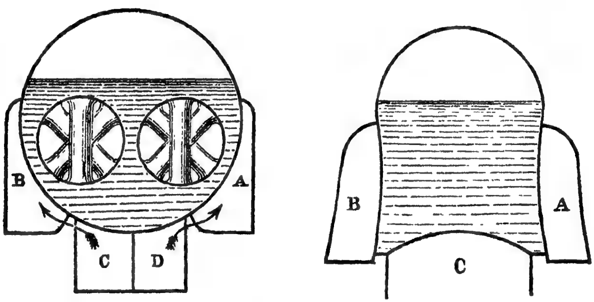


FIG. 101.

would have a steam space of 97 cubic feet, the total heating surface being estimated at 156 square feet. The flues were arranged for what was termed a 'wheel-draught,' that is to say, the heated gases passed under the boiler through C, rose up to the flue A, and came back along one side in order to pass through the flue B along the other side, and so to the chimney,

If such a boiler were subjected to internal bursting pressure, and were capable of altering its form, each of three surfaces, A, B, and C, would be bulged outwards, and the type would approach that of a cylinder. It follows that the peculiar waggon-shaped section can only be preserved by the employment of a sufficient number of wrought iron stays or rods passing from surface to surface, and holding the plates in an immovable position; and

further, that the only part of the shell which can assist itself is the arched top.

A first idea of the Lancashire boiler will be obtained from the sectional sketch. Here the diameter of the shell is supposed to be 7 feet, and that of each tube is 2 feet 9 inches. The water space between the tubes is 5 inches, and that between the tube and the shell is 4 inches. The water level is about that indicated. It is common to place intermediate water pipes across the furnace tubes, as shown in the sketch, for the purpose of intercepting some of the heat of the gases. There are various contrivances of this kind, called water pipes or water pockets. As to the circulation of the heated gases, that is arranged by flues running the whole length of the boiler. The hot gases, passing first along the furnace tubes, dip under the boiler, and return through a single flue having a breadth equal to the radius of the shell. Then the gas from the side C rises to B and passes back along the outside shell, while that from D passes into A and returns in like manner. The gases meet again at the end of the boiler and proceed horizontally on their way to the chimney-stack, but before reaching it they may encounter some form of economiser or apparatus for heating the feed water, consisting of a group of water pipes placed in the main flue which absorb heat from the waste gases, and return it to the boiler by raising the temperature of the feed water, say to 240° F. or thereabouts.

The arch of the boiler is carefully protected, first by a layer of non-conducting substance, and secondly by an arch of brickwork.

With cylindrical boilers there is a difficulty about strengthening the ends. Theory would tell us to make the ends hemispherical, when their strength would be as much as twice that of the cylindrical sides. There is, however, a practical objection to forming a hemispherical or 'egg-end,' as it is called, from the boiler plate, and the result is that the ends are commonly made of flat plate, which is strengthened artificially in such a manner as to give security against danger.

The use of high-pressure steam was advocated by Trevithick and Woolf, and both these engineers adopted the cylindrical form of shell, Trevithick originating the Cornish boiler, with internal firing, and Woolf constructing a boiler in 1803 composed of nine

cast-iron pipes, each 12 inches in diameter, exposed externally to the direct heat of the fire, and connected above to a larger pipe, which again was in free communication with a large cylindrical receiver forming the steam chest.

In order to show what may be done in this direction we refer to Perkins's steam boiler, consisting entirely of wrought-iron tubes, each $2\frac{1}{2}$ inches internal diameter and 3 inches external diameter. The boiler is made up of five layers of these tubes, all placed horizontally, and connected together by small vertical wrought-iron tubes, with screwed gaspipe joints. It was designed for an engine working at a pressure of 500 lbs. per sq. inch. The influence of size must not be disregarded. Thus Mr. Perkins states that the strain upon the material of a cylindrical boiler 5 feet in diameter, and with steam at 19 lbs. pressure, is the same as in one of these tubes at 500 lbs. pressure.

THE STRENGTH OF CYLINDERS UNDER INTERNAL PRESSURE.

131. The strength of a cylindrical boiler to resist internal pressure is calculated as follows :—

Let r be the radius of the inner surface of a cylinder composed of a metal which can support a tensile strain of W lbs. per sq. inch. Let e be the thickness of the shell, and p the pressure of the enclosed fluid.

We shall confine our attention to a small rectangular piece of the shell, whose sides are x, y, and whose thickness is e, and which is under the action of a force $p\,x\,y$ acting outwards on the area $x\,y$, as well as to the forces P, P, Q, Q, marked in the sketch.

Looking sideways at the slice, as in the right-hand figure, we observe that the two forces Q, Q, acting tangentially at the ends of the arc A B, balance $p\,x\,y$. Let A C B $= 2\,\theta$, then

$$2\,\mathrm{Q}\sin\theta = p\,x\,y.$$

But A B $= y$, $\therefore \sin\theta = \frac{y}{2\,r}$ very nearly; also a bar 1 sq. inch in sectional area supports W lbs. $\therefore e\,x$ sq. inches support $\mathrm{W}\,e\,x$ lbs., whence $\mathrm{Q} = \mathrm{W}\,e\,x$.

$$\therefore 2\,\mathrm{W}\,e\,x \times \frac{y}{2\,r} = p\,x\,y, \text{ or } e = \frac{p\,r}{\mathrm{W}}$$

This gives the thickness for supporting a given circumferential pressure, and the conclusion is that the thickness must increase in the same proportion as the diameter, in order to resist the strain on a longitudinal section.

Taking the expression for Q, viz., $\text{W}ex$, and substituting the value of e just found, it appears that $\text{Q} = \text{W}x \times \frac{pr}{\text{W}} = prx.$

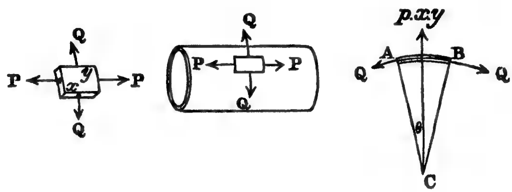


FIG. 102.

We have next to consider the strain produced by the forces P P, which tend to tear the shell asunder along a transverse section. Such a strain is produced by the pressure on the flat ends.

The pressure on one flat end $= p \times \pi r^2$, and this pressure is supported by the cohesive strength of the material in a transverse section whose area is $2\pi r e$. As before, $2\pi r e$ square inches will support $2\pi r e \text{W}$ lbs.,

$$\therefore\ 2\pi r e \text{W} = p\pi r^2, \text{ or } e = \frac{pr}{2\text{W}},$$

which is exactly half the value before obtained. To put this in another way, since P is the strain on an area ey, being part of a ring whose area is $2\pi r e$, it is apparent that

$$\frac{\text{P}}{\pi r^2 p} = \frac{ey}{2\pi r e}, \text{ or } \text{P} = \frac{pry}{2}.$$

Cor. Let $x = y = 1$. $\therefore\ \text{P} = \frac{pr}{2}$, $\text{Q} = pr$, whence $\text{Q} = 2\,\text{P}$,

or the strain on a longitudinal section (per linear inch for any thickness) is twice that on a transverse section.

132. The strain on a longitudinal section per linear inch of the material of a cylindrical boiler may also be found by a simple application of a law of fluid pressure.

Let D E H B A represent a portion of a cylindrical boiler, D E A, C H B being two planes perpendicular to its axis, and D C B A being a plane containing its axis. The property of fluid pressure relied on is that the whole bursting strain on the metal strips A B and D C is the same as the pressure of the enclosed fluid on the area D C B A.

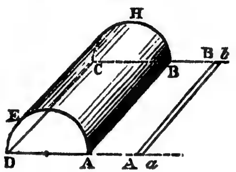


FIG. 103.

Let A B $= x$, D A $= 2r$, and let p be the pressure of the fluid or steam. Further, let e be the thickness of the shell (a section at A B being really represented by A a b B, where A a = B b = e), and let W be the tensile strength of the material per square inch of section. Hence A B and C D together can support 2 W ex lbs.

Now the pressure on each unit of area of the curved surface of the cylinder can everywhere be resolved into two components, one perpendicular to the plane D C B A, and the other parallel to it. Of these components the sum of the former is the pressure on D C B A, and the sum of the latter is zero; hence

$$p \times \text{area DCBA} = \text{strain on AB} + \text{strain on DC},$$

$$\text{or } p \times x \times 2r = \text{W}ex + \text{W}ex$$

$$\therefore p = \frac{\text{W}e}{r}.$$

The material of the shell of a full-sized Lancashire boiler is usually wrought iron, but steel plates are frequently introduced in the furnace tubes, especially in the part around the fire. The thickness of the iron plates would be $\frac{7}{16}$ inch for a pressure of 75 lbs. per sq. inch, or $\frac{9}{16}$ for 100 lbs., and the width of a plate is (say) 3 feet.

As to the strength of boiler-plate the general rule is that a rolled plate is less strong per square inch of section than a thick bar of the same iron. Also the reduction of strength is more marked in the transverse than in the longitudinal direction. There is a further subtraction from strength by riveting; and according

to Sir W. Fairbairn the breaking strains of riveted joints of boiler plate are estimated somewhat as follows :—

	Pounds.
Iron	50,000
Double riveted joint	35,000
Single riveted joints	28,000

per square inch of section of plate.

Since the plates after rolling are stronger in the direction in which they are rolled than transversely, it is apparent that they should be so disposed that the direction of greatest strength should encounter the greatest strain.

But the strain on the longitudinal section is greater than that on the transverse, and hence the plates, which may be 3 feet wide, are wrapped round the circumference, being laid in three lengths, in order that the longitudinal seams may clear the brickwork seatings. As a consequence of the theoretical disproportion between the two strains, it is further recommended that the longitudinal seams should be *double*-riveted with $\frac{3}{4}$-inch rivets, pitched about $2\frac{1}{2}$ inches longitudinally and 2 inches diagonally. The transverse seams are single-riveted, the pitch being 2 inches. To double-rivet them would appear to add but little to the strength of the boiler, though it would increase its weight and cost.

The furnace tubes diminish the area of the flat ends, and relieve the pressure tending to rupture the material on a transverse section; they further act as stays for holding the ends together. On both these accounts a boiler with internal tubes becomes stronger than it would be without the tubes, so far as transverse rupture is concerned. The flat ends remain, however, a source of anxiety, and in order to support them gusset stays and tie rods are employed, as to which something will be said, after the disturbing action of heat has been noticed.

Ex. Let a boiler be 7 feet in diameter, with two internal flues, each 33 inches in diameter, and made of boiler plate $\frac{1}{2}$ inch thick. To find the bursting pressures (1) along a longitudinal and (2) along a transverse section :

We shall assume that $w = 35{,}000$ for the double-riveted or longitudinal joints, and $w' = 28{,}000$ for the single-riveted or transverse joints.

Let p be the bursting pressure for a longitudinal section,

$$\text{then } p = \frac{we}{r} = \frac{35{,}000}{2 \times 42} = 416{\cdot}6 \text{ lbs.}$$

Calling p' the value of p for a transverse section :—

Circumference of shell	= 263·89	inches
" each flue	= 103·67	"
Making a total of . .	471·23	

Now, the tensile strength of a strip of iron single-riveted, 471·23 by $\frac{1}{2}$ inches in area, is

$$28{,}000 \times 471{\cdot}23 \times \tfrac{1}{2} \text{ lbs.}$$

$$\therefore p' \times 3{,}831{\cdot}17 = 28{,}000 \times 471.2 \times \tfrac{1}{2}$$

$$\therefore p' = 1{,}722 \text{ lbs.}$$

From which we infer that the boiler is more than four times stronger along a transverse than a longitudinal section. These numbers show the extent to which the flues strengthen the shell, and confirm the statement which preceded the computation.

EFFECT OF HEAT.

133. The wear and ultimate strength of a boiler is greatly influenced by adopting a construction which shall provide for the inevitable changes of form caused by unequal expansion and contraction due to changes in temperature. Heat is motion, and as soon as the fire inside a furnace tube is lighted the metal on the top becomes more heated than the under surface, and the tube arches itself, in consequence of the greater expansion of the hotter portion. And not only so, but the tube lengthens as a whole, and the flat ends bulge outwards. Finally, the water becomes heated, the whole structure elongates, and, unless sufficient allowance be made for these pulsating movements, straining will occur, which may possibly end in rupture.

The linear expansion of wrought iron (soft forged) under the action of heat is stated by Dr. Percy to be ·0012204 for a rise in temperature from 0° C. to 100° C.

Thus a bar of iron, 30 feet long, expands about $\frac{7}{10}$ inch for a rise in temperature of 270° F.

The expansion of the parts of a boiler as caused by heat is, of course, capable of accurate measurement, and in particular the so-called 'hogging' of a furnace tube has been observed by applying

three gauge rods attached at equal distances along the crown of the tube. Each rod is carried vertically upwards, and passes through a stuffing-box in the shell of the boiler, whereby it has been possible to observe very accurately the distortion of the tube. One boiler experimented on was 28 feet long, and it was found that the tube rose $\frac{3}{8}$ inch when the flame passed around the boiler in the ordinary way along the side flues, and that it rose $\frac{1}{2}$ inch when the flame was carried directly into the chimney without heating the outer shell. The gauge rod at one-fourth the length of the boiler from the front end rose as much as that, and in one case it rose $\frac{1}{16}$ inch more. Also the colder the water at starting the greater was the distortion, and generally the action was more severe just after lighting the fires. As soon as the whole of the water became permanently heated the gauge rods retired to their primary position, the distortion of the tubes seldom lasting for more than an hour. It is most instructive to read an account of the Lancashire boiler as given by Mr. Fletcher, at a recent meeting of the Institution of Mechanical Engineers (A.D. 1876), where all these points are fully discussed. Our object is to point out to the student that a boiler 30 feet long is a large piece of apparatus constrained to obey and exemplify the laws of the communication of heat, and that its structure and design should have reference to these laws. Thus Mr. Fletcher remarks that when furnace tubes are lashed to the shell they often tear themselves away from it, and that in one case, where a furnace tube was supported by means of a stay tying it to the top of the shell, it was found that the thrust of the tube had crumpled up the stay by compression and had broken it by an upward thrust, thus showing how little need there was for suspending the tube by a rod in order to prevent it from drooping.

STAYS AND TIE RODS.

134. We have seen that the double-flued boiler was introduced by Fairbairn, and to that engineer we are indebted for a method of staying the flat ends which has been generally adopted. In 1856 Sir W. Fairbairn recommended that boilers should be constructed of a cylindrical form, in order to obtain as nearly as possible the

maximum strength, and that where flat ends were used they should be composed of plates one-half thicker than those forming the circumference. The flues, if two in number, should be of the same thickness as the exterior shell, and the flat ends of the boiler should be carefully stayed with gussets of triangular plates firmly connected with the shell by angle irons. Sir W. Fairbairn stated that in his opinion gussets are infinitely better and more certain in their action and retaining powers than stay rods; also, that when gussets were used they should be placed in lines diverging from the centre of the boiler.

As to longitudinal stays, they are simply rods of iron, running from end to end and secured with double nuts, one inside the boiler and one outside. In the Lancashire boiler there are commonly two such stays, placed about 14 inches above the furnace crowns, one on each side of the central vertical line, and near together.

The annexed drawing will give an idea of the manner in which the flat end of a boiler is strengthened by gusset stays. The portion shown is that most remote from the furnace. The internal tube is represented by B B, and there is a vertical water pipe P, to which reference was made in a previous sketch. The furnace tube is made in lengths united by Adamson's flanged seam (see Art. 135). The gusset stays are shown at A, A, A. They appear in the drawing to come close to the tubes, but that is because the section of the tube is shown on one side of its true position, in order to bring it into the drawing. A longitudinal slice through the centre of the boiler would not indicate the furnace tube at all, and the latter is merely projected on the actual sectional drawing, in order to make one sketch perform double duty. The real position of the gusset stays will be apparent from an inspection of fig. 106, where they are indicated by

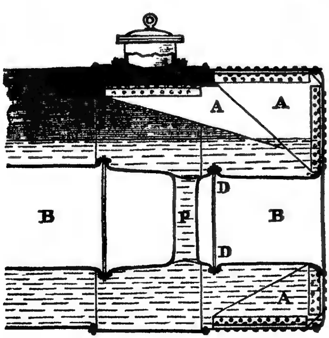


FIG. 104.

dotted lines. It is usually considered that there should be five gusset stays on the large upper area of the flat end, and they would then take the positions marked. It will be noted that the middle stay supports the central area, just where the flat plate requires additional support, and also where it can be firmly held without preventing the movement of the furnace tubes. It is important that the ends of a boiler should be elastic, in order that they may yield to expansion, in which case the hogging of the tube would not be so great; the conclusion being that the greater the rigidity of the ends the greater is the strain upon the tube. If the gusset stays come too near the tube a grooving action may be set up in the iron plate forming the end.

It appears that such grooves are produced inside the boiler and all round the furnace mouth. They are believed to be due to an action which is partly mechanical and partly chemical. The furnace tubes are continually expanding and contracting from the alternations of heat and cold, and there should be sufficient width of plate between the tubes, as well as between the circumference of the tubes and the ends of the gussets, to allow this bulging action to go on without fatiguing the metal.

Mr. Fletcher recommends that the end plates of boilers, to be used at a pressure of 75 lbs. per sq. inch, should be $\frac{1}{2}$ inch in thickness, increasing to $\frac{9}{16}$ inch for increased pressure within moderate limits, excessive thickness being undesirable, as confining or restraining the necessary movement of the furnace tubes. The object is to strengthen the end plate and yet to preserve its elasticity; and in carrying out this intention it is a rule to attach the plate at the front of the boiler to the shell by external angle iron This mode of construction is not, however, adopted at the opposite end.

135. The furnace flues are a vulnerable part of the boiler, inasmuch as they are liable to yield by collapsing unless sufficiently strengthened.

The subject of strengthening the internal tubes of the Lancashire boiler was investigated by Sir W. Fairbairn, whose experiments led to the following conclusions :—

1. The strength of a tube to resist collapse by external pressure is inversely as its diameter.

2. The strength varies inversely as the length.
3. The collapsing pressure in pounds per sq. inch

$$= 806{,}300 \times \frac{(\text{thickness in inches.})^{2 \cdot 19}}{\text{Length in ft.} \times \text{diam. in ins.}}$$

In these experiments the ends of the tubes were firmly attached to rigid plates, and the vessel in which the compressing force was applied was a cast-iron cylinder 8 feet long, 28 inches in diameter, and 2 inches thick, which could be safely strained as far as 500 lbs. per sq. inch. Into this cylinder air was forced by a pump, and produced any required pressure on the surface of a quantity of water which nearly filled the cylinder, and in which the tube under trial was completely immersed. There were two gauges for reading the pressures, and a safety valve in addition, which was loaded by a weight.

Some of the experiments followed the law as stated above pretty closely. Thus, in the case of a 4-inch tube of thickness ·043 inch, and of length 30 inches, the collapsing pressure per sq. inch was 93 lbs., whereas when the tube was 60 inches long the collapsing pressure fell to 47 lbs., which is very nearly one-half the former value, and verifies the law that the strength is (other things being equal) inversely as the length.

Since log. 806300 = 5·9064967 = 5·9065 approximately, and since the thickness of boiler tube is generally a fraction of an inch, it will be convenient to modify the formula as follows :—

Let P be the collapsing pressure per sq. inch of section, e the thickness of the plate, L the length in feet, D the diameter in inches; then

$$\begin{aligned} \text{Log. } P &= 5{\cdot}9065 + 2{\cdot}19 \log. e - \log. L \times D \\ &= 1{\cdot}5265 + 2{\cdot}19\,(2 + \log. e) - \log. L \times D \\ &= 1{\cdot}5265 + 2{\cdot}19 \log. 100\,e - \log. L \times D. \end{aligned}$$

In this shape the formula is applied without difficulty, and it may be further simplified by putting it under the form

$$P = 806{,}300 \times \frac{e^2}{L \times D}$$

Ex. Let the flue be 36 inches in diameter, 10 feet long, and ½ inch thick.

Then log. P = 1·5265 + 2·19 log. 50 — log. 360 = log. 491.

Whence the collapsing pressure would be 491 lbs. and the safe working pressure $\frac{491}{6}$ or 82 lbs. Taking the formula with 2 in the place of 2·19, we have collapsing pressure = 560 lbs.

The Board of Trade has adopted a rule which dispenses with logarithms, and is the following :—

$$\text{Working pressure in lbs. per sq. inch} = 90{,}000 \times \frac{t^2}{(L+1) \times D}.$$

This rule is applicable to marine boilers, where the practical limit of length is from 10 to 15 feet.

The experiments made by Sir W. Fairbairn were valuable as calling attention to a material subject connected with the construction of boilers; but it appears that a special contrivance for strengthening furnace flues, while allowing at the same time for their expansion and contraction, had been originated some years prior to the researches to which reference has been made. At a meeting of the Institution of Mechanical Engineers held in 1876 Mr. Adamson stated that he had first employed a 'flanged seam,' as it is termed, for the strengthening of furnace tubes as early as the year 1851. The annexed sketch exhibits three forms of joint as applicable to tubes subjected to external pressure. The first, marked A, consists of a ring of T-iron riveted as shown. It is abundantly strong and is in a form which has been adopted for centuries past in strengthening guns. The weakness of a tube to resist a bursting pressure on a longitudinal section has been already demonstrated, and a common method of strengthening it has been to apply parallel rings at intervals along its length. In this way steam cylinders of great length, which are subjected alternately to a bursting and compressing pressure, have been strengthened. Everyone is aware of the accession of strength caused by the flange of a pipe.

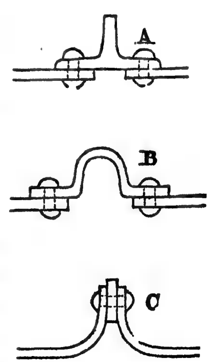


FIG. 105.

Since action and reaction are equal and opposite, we might have anticipated that a form of tube constructed so as to withstand a

bursting pressure from within, would also be the form best adapted for resisting a collapsing pressure from without. The difficulty of calculation in the latter case arises from the liability to deformation, which is soon set up, after which theory is of little use in enabling us to predict a result.

But although the joint A has ample strength it is deficient in another quality which is of importance, viz., it does not permit any alteration of length. The whole furnace tube is rigid, and expands or contracts as one piece.

Whereas, in the joint marked B the expansion or contraction of each length of the tube is provided for by the arched or corrugated piece, and here there is increased strength combined with power of expanding or contracting freely.

In the joint marked C, which is known as 'Adamson's flanged joint,' there is the strength of the T-iron directly combined with the curved end, which allows of unimpeded expansion or contraction. The arrangement is most convenient and effective, and is particularly valuable as giving a seam where the rivets are protected from the furnace gases, and are, in fact, immersed in water, one consequence of the construction being that the joint will bear intense heat much better than any other where the rivets are exposed.

FITTINGS FOR A BOILER.

136. Those fittings which require frequent access are arranged so as to be within reach of the attendant when standing in front of the boiler. They will be enumerated in the order in which they would probably attract attention, and some are to be seen in the sketch annexed.

1. The pipe for supplying the feed-water is a vertical pipe C D, which branches off into the boiler on one side above the level of the furnace crowns, and is carried along for (say) 12 feet in a horizontal direction, the last 4 feet of its length being perforated. The importance of introducing the feed-water in such a manner as to avoid local contraction should now be pointed out.

Suppose that a supply of feed-water, not previously heated, is introduced at the bottom of a boiler. The water enters after the whole structure has been heated, and has therefore become

larger throughout. The effect of the colder water is to cause contraction of the under surface, but the rest of the boiler is unwilling to yield, and a straining action is set up which tries all the joints. Whether the upper portion is unduly heated at first, in anticipation of the general enlargement which finally takes place, or whether after the whole structure has been heated the lower portion becomes cooled, the effect is equally bad—one part of the boiler is pulling against the other, and the joints are strained. Hence the better plan appears to be to carry the

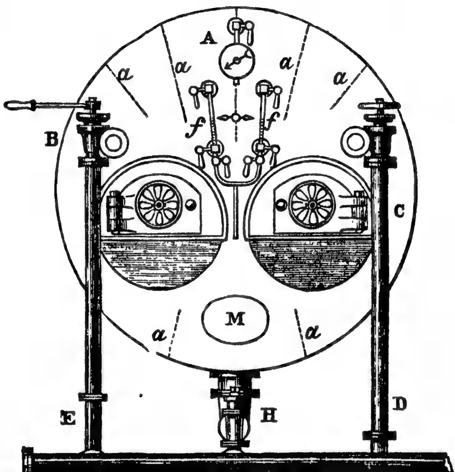


FIG. 106.

feed-water for some distance along the interior of the boiler, and then to disperse it, so as to moderate as far as possible any inequality of temperature.

On the opposite side of the boiler there is a vertical pipe B E, intended for removing the scum which may have collected in a sediment-catching trough, inside the boiler, with which it communicates.

At the bottom there is a blow-out cock, marked H, for clearing out the water when necessary.

2. The furnace mouth-pieces are fitted with fire-doors, which are provided with some arrangement for admitting a variable supply of air. For example, there may be a ventilating grid, as it is termed, on the outside and a perforated box-plate on the inside, the aggregate area of the air-passages being about 3 sq. inches for each sq. foot of firegrate.

The standard length for the firegrate is 6 feet, with bars about $\frac{3}{4}$ inch thick and $\frac{3}{8}$ inch apart. The bearers are wrought-iron bars, supported on brackets.

3. *The Pressure Gauge.*—A form of gauge very commonly met with has been in use for more than twenty years, and was invented by M. Bourdon, a French engineer. The circumstances attending the application of a new principle in the measurement of fluid pressure show the advantage of reasoning closely upon observed facts. When a discovery is made everyone says how simple it is, and wonders that it was never thought of before. In the present instance M. Bourdon was engaged in repairing the worm-pipe of a still which had become flattened, and he endeavoured to restore its original form by forcing water with a powerful pump into the interior of the tube. In doing so it was observed that the flattened tube tended to uncoil itself, and further experiments showed that the action of uncoiling might be applied in the construction of a pressure gauge.

The sketch (fig. 108) is taken from a model belonging to the School of Mines, and serves to exhibit the action of the gauge as well as to test its accuracy as a measuring instrument. The gauge consists of a flattened tube *e e*, connected at one end with a pipe containing fluid under pressure. The other end of the tube is closed, and is attached to a link connected with a segmental rack which is in gear with a pinion *f*, and thereby moves an index-finger over a scale. The index-finger and the graduations are shown separately in a reverse view of the circular case which contains the tube. At D is an opening into which one end of a force-pump is screwed tightly, so as to fill the tube with compressed air. At H and A are stopcocks, the convenience of which is obvious; and it will be seen that beyond A there is a vertical piece of gas-tubing, which supports an ordinary mercurial siphon gauge. At B there is a cap or nut, which can be unscrewed, so as to admit air,

or to give access to the shorter leg of the gauge when required. Upon opening the stopcocks at A and H and forcing in air by the pump at D, it will be found that the circular tube straightens itself a little and pulls the end of the segmental arc sufficiently to turn the pinion *f* and to rotate the index-finger. When the mercury

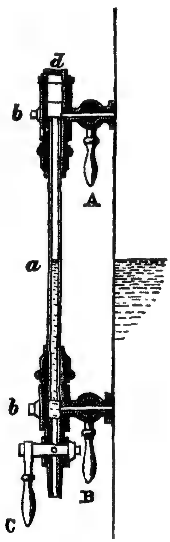


FIG. 107.

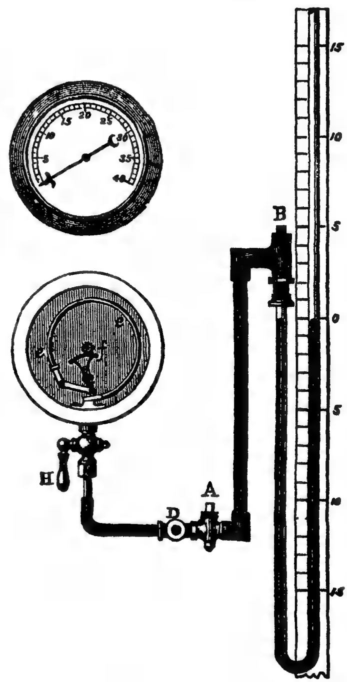


FIG. 108.

sinks through 1 inch in either leg of the siphon it rises also to the same amount in the other leg, and the difference of level is, therefore, 2 inches, which roughly corresponds to 1 lb. in pressure. The graduations of inches on the vertical scale correspond, therefore, to pounds in pressure as read off on the circular dial-plate; and it will be found that the index-finger travels round the

dial in accordance with the rise of mercury in the leg of the siphon. It remains to examine the reason for the straightening of the tube under pressure. One way of looking at the question is based on a theorem in geometry by which it is proved that if a flexible but inextensible surface be deformed in any way, and if *p* be a point in the surface, and *a p b*, *c p d* be the principal sections of the surface made by planes at right angles to each other and passing through the line perpendicular to the surface at the point *p*, the product of the curvatures of the two sections *a b*, *c d* will be a constant quantity. The word 'curvature' is a technical term, and its meaning will be understood when we say that the curvature of a circle is inversely proportional to its radius; also the principal sections referred to are the sections of greatest and least curvature at the point.

The form of the tube *e e* is given in cross-section by the curve *c p d*, and the line *a p b* may be taken to represent the curving of *e e* in the direction of its length. If the product of the curvatures—viz., those in *a b* and *c d* respectively—be constant, it will follow that when one increases the other must decrease, and conversely. That is to say, if the tube *e e* becomes more curved in the direction *c p d*, it will become less curved in the direction *a p b*. But the effect of air under pressure is to bulge *c p d* outwards, and to make it more convex, or to give it a larger curvature, and the direct result is that the tube *e e* straightens and its end moves outwards.

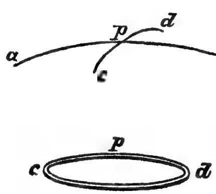


FIG. 109.

It is easy to show that such an action will certainly occur, for if we bend a vulcanised indiarubber tube it will become more and more flat, and will finally straighten in the direction across that in which it is being bent.

The gauge as constructed is subject to the objection that water will collect in the lower end of the tube, thereby rendering the metal liable to corrosion, and in order to obviate this result a semicircular tube is sometimes employed, from which any water formed by condensed steam will drain out. But a shorter tube limits the sensitiveness of the instrument and makes it necessary

that the movement should be magnified in a greater degree. As to the material, that is commonly thin brass, but sometimes the tube is made of steel.

Another form of gauge which has been extensively used is the 'Smith gauge,' where a small diaphragm of indiarubber is confined by a flange at the top of a tube, and is acted upon directly by the steam on one side. The yielding of the diaphragm is restrained by a volute spring of steel, wound round and round in a close flat spiral like the spring of a watch, but with its central portion projecting a little downwards when at rest, so as to cause the diaphragm to be somewhat convex on the steam side when the pressure is cut off. At medium pressures the spring becomes quite flat, and at extreme pressures it curves inwards. The centre of the spring is attached to an upright rod terminating in a straight rack, which actuates a pinion and gives motion to the index-finger.

4. The *water-gauges*, marked *f* in the drawing. Of these there are two, so that one may act as a check on the other.

In fig. 107 there is also a sectional elevation of a water gauge, in which the outline of the instrument is shown, but no attempt is made to indicate the separate metal pieces, which are screwed together, so as to permit of the tube being removed and packed. All that is shown is a glass tube *a*, inserted into the supports by removing the cap *d*, and packed so as to be steam and water tight. There are three stopcocks—viz., at A, B, C—which can be opened or closed, at pleasure. Ordinarily C is closed, while A and B remain open; but, if required, any of the passages can be blown through by steam or water from the boiler.

Gauge-cocks answer the same purpose as the glass tube in the water gauge. They are three small cocks, placed one above the other, and opening directly into the boiler, the middle one being on the line of the usual water level.

5. *Connecting pipes*, such as the feed-pipe, or main steam-pipe, should be elastic, so as to allow of some movement under changes of temperature. Thus a copper elbow-pipe or a wrought-iron horseshoe-shaped pipe may be introduced where necessary, and will yield by bending, so as to relieve the thrust or pull caused by expansion or contraction. So, again, if the main steam-pipe be carried across the boilers and bolted direct to the steam junction-

valve the joints would be strained by the rising or falling of the boilers when heated and cooled. To prevent any injurious action from this cause a springing length is introduced between the steam stop-valve (which is secured just above the boiler) and the main steam-pipe.

Many boilers have a steam dome, from which the supply of steam is drawn, but in others it is omitted, and an internal perforated pipe or *anti-priming* pipe is adopted instead of the dome.

SAFETY-VALVES.

137. The ordinary safety-valve, held down by a lever and weight, was invented by Papin before the date of Newcomen's engine, and the annexed sketch, taken from one of Dr. Anderson's lecture diagrams, shows the manner in which it is customary to explain this well-known application of the principle of the lever

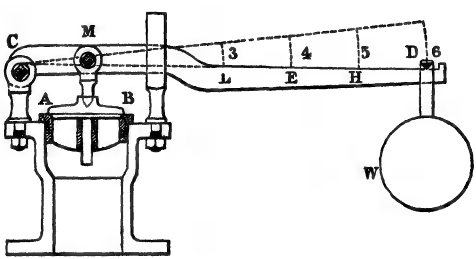


FIG. 110.

The general construction is apparent from the drawing, the valve A B being pressed upon its seat by the action of the weight W hung at the end of the arm C D. The fulcrum of the lever is at C, and the arm C D is supposed, for simplicity, in the first instance to have no weight; also C M = 1, and the points L, E, H, D are at distances from C respectively represented by the numbers 3, 4, 5, and 6, whence it follows that if the valve be lifted through a small space the motion of D will be six times that of M, and so for the other points, L, E, H, the numbers 3, 4, 5 indicating the relative

motions of these respective points as compared with that of the valve itself.

Let the area of the valve be 20 square inches, and let W be 200 lbs.

1. Let W be hung at D; then by the principle of work,

$$\text{pressure of steam on AB} \times 1 = W \times 6;$$

$$\text{or, pressure of steam per square inch} \times 20 = 200 \times 6,$$

$$\therefore \text{ pressure of steam per square inch} = 60 \text{ lbs.}$$

2. Let W be hung at H; then

$$\text{pressure per square inch} \times 20 = W \times 5 = 200 \times 5,$$

$$\therefore \text{ pressure of steam per square inch} = 50 \text{ lbs.},$$

and so for the remaining positions of W.

Note.—It is necessary to take into account both the weight of the lever and that of the valve. As to the former, it is clear that the weight of the lever makes a slight increase to W, which can be found by trial, remembering that the product of the weight of the lever into the distance of its centre of gravity from C is equal to the product of CD into the increase of W. And this latter can, therefore, be found when we know the weight of the lever and the position of its centre of gravity. The problem is that occurring in the case of an ordinary steelyard. As to the weight of the valve, that is merely to be added to the load on AB, produced by W and the weight of the lever.

138. The construction of a safety-valve may be varied from its original type in two principal ways :—

1. The lever may be retained, but the weight may be replaced by a spring balance. This construction is very commonly to be seen in the case of locomotive boilers, and the substitution of a spring for a weight is an obvious alteration.

We may here examine a form of compound safety-valve, which is different from the ordinary valve, and which is applied on the North-Western Railway. It appears that in 1855 Mr. Ramsbottom obtained a patent (No. 1,299) for an improved mode of loading safety-valves, wherein 'two safety-valves, connected by a cross-bar, were placed at such a distance apart as to admit of a spring or weight being applied between the two of sufficient power to resist the pressure on both valves.' By this arrangement the ordi-

nary spring balance was dispensed with, and the pressure on the valves, when once adjusted, could not be increased. Also the crossbar was prolonged at one end, in order to serve as a handle for feeling the working condition of the valves.

Mr. Ramsbottom considers that the range of lift for blowing off (owing to the non-intervention of levers between the valve and spring by which it is loaded, and regard being had to the dimensions of the spring itself) is here about three times as great as in the ordinary lever and spring-balance valve.

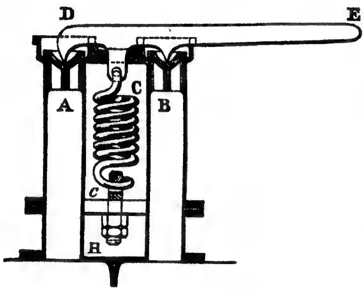


FIG. 111.

The sketch is taken from the specification of the patent. The valves A and B are shown resting on their seats, being made with conical recesses to receive the points of the cross-bar D E. The spring is of sufficient power to hold down both valves, and the point of its attachment to the crossbar at C is below the bearing points of the same bar on the respective valves. The tension of the spring is adjusted by a bridle and set screws at H.

When the pressure of the steam overcomes the resistance of the spring the valves are raised; and if one, as A, rises more than the other, the spring leans towards A a little, by reason that the point of attachment of the spring is lower than the point of the lever bearing on the valve, and thus B is relieved from a part of its load. This arrangement tends, therefore, to secure the simultaneous action of both valves.

2. The lever may be dispensed with, and the valve may be loaded by a weight placed directly over it, or may be held down by a spring also applied directly, when we have a 'dead weight' or direct 'spring-loaded' valve.

The examples hitherto given show the common methods of guiding the valve. There is (1) a central pin of some length and small diameter, as in fig. 110; or (2) there are wings radiating from a central axis, as indicated in fig. 111.

Where the weight is applied directly to a valve some guide is necessary, but there is a form of dead weight safety-valve, largely used in stationary engines, where guides are not required ; and inasmuch as they cause friction, and may possibly become jammed it is an advantage to dispense with them.

The contrivance now referred to is known as a 'Cowburn valve,' and the construction is so simple that it will be readily understood without a drawing. The valve is spherical, and is placed on the top of a vertical pipe, outside which there is a casing loaded with annular discs of metal. The centre of gravity of the load is below the surface of the seating, and the result is that the valve, after having been lifted, drops at once into its position, and that no wings or central pin are necessary.

The diameter generally adopted is as much as 4 inches, which requires a load of about 8 cwt. for blowing off at 75 lbs. pressure. The great weight of the load is an element of security, as any addition which materially varied the steam pressure could only be obtained by putting on a weight the size of which would at once attract observation. In practice the weights are annular rings, and the shell on which they rest is cast with mouldings around it, near the bottom, which present the same appearance, the whole being so adjusted that each moulding as well as each annular plate represents 5 lbs. per square inch in the total pressure of the steam within the boiler.

Where the valve lever is held down by a spring the proportions of the lever are commonly arranged so that 1 lb. tension of the spring as graduated is equal to 1 lb. per square inch in the pressure on the valve.

139. By an ingenious variation in the construction of a safety-valve it is possible to arrange that the valve shall blow off, not only when the pressure of the steam rises beyond a certain limit, but also when the level of the water in the boiler sinks below a given point. The apparatus is then a combination of two distinct parts, each operating independently of the other. Take, for example, the low-water safety-valve by Mr. Hopkinson. This may consist of an outer valve 5 inches in diameter, in the form of an annulus or ring, which would be held down by a lever and weight, and would be precisely the same in its action as an ordinary safety-

valve. The central area of the ring is filled up with a circular disc-valve (say) $2\frac{1}{2}$ inches in diameter, which is loaded by a dead weight hanging inside the boiler. This central valve cannot rise until the pressure of the steam overcomes the weight; and we have, therefore, as far as the description goes at present, an ordinary safety-valve, 5 inches in diameter, but made of two parts, separately loaded.

Inside the boiler, and suspended from the crown thereof, is a lever, having a slab of stone at one end, and a weight, sufficient to counterbalance the weight of the slab when immersed in water, supported at the other end. Under these circumstances the lever is balanced so long as the stone slab or float is just immersed. The line of direction of the spindle of the smaller valve—viz., that $2\frac{1}{2}$ inches in diameter—passes near the fulcrum of the lever carrying the float and counterpoise, and it is arranged that when the water in the boiler sinks below a certain level the depression of the stone float raises the opposite arm of the lever sufficiently to lift the smaller valve together with the dead weight hanging within the boiler, and thereby opens a passage for the escape of steam. Thus the valve fulfils the double purpose required of it.

140. One practical difficulty connected with the safety-valve arises from the deficiency of lift when the steam is blowing off, whereby the internal steam pressure may considerably exceed that to which the valve is loaded.

This has been matter of common observation for many years past, and various modifications have been proposed in order to remedy the defect. For example, in 1856 Mr. Hawthorn made some experiments on the Newcastle and Carlisle Railway, where two valves were fitted to the same locomotive boiler, viz., (1) a common mitre-valve, 4 inches in diameter, and (2) an annular safety-valve, as patented by himself in 1854, No. 2,582. The heating surface was here 63·52 sq. feet in the firebox, and 681·25 sq. feet in the tubes, making a total of 744·77 sq. feet. Also, each valve was loaded so as to lift at a pressure of 58 lbs. per sq. inch, as indicated by Smith's gauge.

When the annular valve was locked down and the mitre-valve was open, the steam pressure rose to 68 lbs. on the gauge, showing an excess of pressure of 10 lbs. The steam was now blowing off strongly at 68 lbs., and the annular valve was released,

while the mitre-value was locked. The steam pressure immediately fell to 60½ lbs., at which it remained without change. Other experiments of the same kind gave similar results; and in particular in the case of a goods engine for the East Indian Railway, having two mitre-valves of 3½ inches in diameter, and loaded to 105 lbs., the heating surface being 102 sq. feet in the firebox, and 1035 in the tubes, it was found that the pressure rose to 130 lbs.

On this subject Mr. Webb has stated, at a recent meeting of the Mechanical Engineers, that, with the Ramsbottom system of two valves 3 inches in diameter, he had never found the steam to rise in locomotive boilers more than 5 or 6 lbs. above the pressure at which the valve was set to blow off.

He has also described an experiment which deserves attention, viz., that in the case of a locomotive boiler, when hard fired and with a perfectly open outlet pipe for the escape of steam one inch in diameter, it was possible to raise the steam pressure to something like 10 lbs. above the proper pressure, whereas with a pipe 1¼ inches in diameter 'he could not raise the steam pressure at all.'

It appears to be considered that two causes are at work to produce this excess of internal steam pressure when blowing off, viz., (1) the increased resistance of the spring as due to the lift of the valve, and (2) some unexplained action of the escaping steam in relieving the pressure on the under surface of the valve.

Mr. Naylor has accordingly patented (A.D. 1863, No. 1,830) an improved valve, wherein a bent lever of the first order is interposed between the valve and the spring, it being arranged that the leverage on the side of the spring shall become less as the valve rises, whereby the defect caused by the spring is got rid of, and where it may easily happen that the pressure of the spring on the valve when fully open is rather less than when it rests upon its seat.

ON THE BURNING OF FUEL IN THE FURNACE OF A BOILER.

141. It being agreed that heat is the agent which does work in an engine, and that steam, air, or vapour are but the instruments for transmitting the motion of heat to the machinery, our object will be to store up in an elastic working substance the heat derived from fuel, and to guard against loss as far as possible.

As a general rule *chemical combination* is accompanied by the evolution or production of heat, and *chemical decomposition* by the disappearance of heat equal in amount to that produced during the previous combination of the elements which are undergoing separation.

Combustion, or burning, is the name given to rapid chemical combination attended with the evolution of intense heat.

It is necessary to bear these facts in mind in estimating the heating effect of fuel. Thus, where hydrogen and oxygen exist in coal in the proportion necessary for forming water (viz., one of hydrogen to eight of oxygen by weight), it is usual to assume that they do not influence the heat of combustion. The hydrogen is taken to have been already burnt in oxygen. In coal there may be 5 per cent. of hydrogen and 4 per cent. of oxygen; this would leave 4½ per cent. of hydrogen available for heating purposes.

There appear to be exceptions to the above rule, and Dr. Percy gives the results of an experiment where two coals closely agreeing in ultimate composition have been found to differ by 5 per cent. in calorific power.

The composition of various kinds of coal is given by Dr. Percy, in his work on fuel, and it is well known that the differences in the constituent parts of coal are very great, and give rise to qualities of various kinds which influence the selection to be made for heating purposes. Taking examples of an analysis of coal, we find—

Locality of Coal	Carb.	Hyd.	Ox. and Nit.	Sulph.	Ash	Water
Lancashire	75·90	5·14	10·11	·93	2·02	5·90
Northumberland . . .	81·41	5·83	9·95	·74	2·07	1·35
Derbyshire	83·18	4·76	6·79	1·42	1·70	2·15
Anthracite, South Wales .	90·39	3·28	3·81	·91	1·61	2·0

The heat given out in the burning of hydyogen and carbon is estimated as follows :—

	Units of heat.
1 lb. hydrogen consumes about 36 lbs. air, and gives out .	62,032
„ carbon, burnt to CO, „ 6 lbs. „ „ .	4,452
„ carbon, burnt to CO_2 „ 12 lbs. „ „ .	14,545

According to Dr. Percy the *calorific power* of a substance is the number of units of heat produced by the combustion of a unit of weight of the substance; and if the unit of heat be defined according to the Centigrade scale,

Calorific power of hydrogen	is	34,462		
" " carbon	"	2,473	when burnt to	. CO.
" " carbon	"	8,080,	"	. CO_2

Also 1 lb. of hydrogen	evaporates	64·2	lbs. of water	at 212° F.
" carbon burnt to CO	"	4·6	"	"
" carbon burnt to CO_2	"	15	"	"

It does not appear that the absolute heat of combustion can be increased, but it is easy to pile up the waves of heat in an enclosed space, and thereby to increase wonderfully the apparent power of the combustion.

Upon this point we may refer to a lecture experiment by Faraday, who showed that it was possible to melt platinum in the flame of a common candle. As to the properties of platinum Dr. W. A. Miller states 'that platinum resists the highest heat of the forge, and can only be fused by the voltaic battery or by the oxy-hydrogen blowpipe.' Any attempt, therefore, to melt it by an open flame would appear to be hopeless. But Faraday's proposition was that the heat of burning hydrogen is the same wherever it is produced, and he operated with a platinum wire attenuated to a degree quite beyond the reach of ordinary manipulation, when it was found that the end of the wire was actually melted and ran into a little solid bead, which could be seen when magnified.

The furnace may be looked upon as a large chemical apparatus in which coal and air are to be mixed together in the proportion best adapted for burning the fuel without waste. In performing this operation an engineer falls very far behind a scientific chemist when operating on a small scale in his laboratory. Thus a chemist, in burning one pound of ordinary coal in a carefully protected chamber, would cause the heat from the fuel to evaporate (say) 14 lbs. of water, whereas the evaporation per pound of coal in a steam boiler seldom exceeds 10 lbs. or 10½ lbs. of water, a common performance being the evaporation of from 6 lbs. to 8 lbs. of water. Looking at the question as one of admixture of fuel and air, the

rough numbers usually quoted on the authority of Rankine are the following :—

For the actual burning of ordinary coal in a furnace 12 lbs. of air are required in order to combine with the constituents of each 1 lb. of coal.

But the gaseous products of combustion must be largely diluted, otherwise the air would not get at the fuel, and for this dilution as much air again is required, making a supply of 24 lbs. of air to each 1 lb. of fuel.

Note.—13 cubic feet of air, at 60° F. and under a pressure of 30 inches of mercury, weigh about 1 lb. Therefore 312 cubic feet of air are required for each 1 lb. of fuel, which comes to nearly 700,000 cubic feet of air for the effective burning of one ton of coal.

That gas and hydrocarbon vapour proceeding from coal require a good supply of air for burning was frequently shown by Faraday in a lecture experiment, and his illustration goes to the substance of the whole matter. The device was to soak a little cotton-wool in any hydrocarbon liquid and set it on fire in a jar of oxygen gas. In such a case the hydrogen devours the oxygen and the flame lights up with dazzling brilliancy, but very soon the supply of oxygen fails, the light becomes less, when all at once, for no apparent reason, the burning wool throws out a dense mass of black flakes which fill the jar in a thick cloud. The quantity of soot ejected would surprise anyone but a chemist, as few would be aware that the unburnt liquid was capable of throwing out such a supply of carbon. It is needless to say that the effect here produced in the jar of oxygen is the same as that occurring in the chimney of a steam boiler when the supply of air is defective, the result being that so frequently seen, viz., the pouring out of dense black smoke into the atmosphere.

The loss of heat from unburnt gases may also take place without being made evident by the issuing of smoke. Thus carbonic oxide (CO) may pass away instead of carbonic acid (CO_2).

142. There have been a great number of inventions relating to the prevention of smoke in steam boilers, which cannot be discussed in the space available, and it may suffice to mention that Watt invented a '*dead plate*'; that is, a horizontal or slightly

inclined plate at the mouth of a furnace, on which each fresh charge of coal is placed, in order to be subjected to a species of preliminary distillation, whereby the hydrocarbons are eliminated before the residual carbon is pushed forward on the furnace bars beyond the plate. This plan, where proper provision is made for the supply of air, appears to obviate the production of smoke as effectually as any other contrivance. In burning anthracite a dead plate is said to be useful for heating the fuel gradually, as otherwise it would fly into small pieces, causing waste.

There is also a class of contrivances where mechanical feeding takes the place of hand labour, the grate bars being connected so as to form an endless chain, or the oscillation of alternate bars throwing forward the fuel by a rocking movement.

Another class of contrivances deals with the supply of air both above the fuel, to burn the gas, and below it, to burn the carbon. The supply of air through the furnace doors may be regulated by self-closing ventilators, like Venetian blinds, and the air itself is, by the arrangement of the plates, warmed as it enters the furnace.

Another plan depends on the double furnace with alternate firing. It is apparent that in the Lancashire boiler with two furnace tubes it is possible to keep one furnace always clear, and to burn, by means of the gas proceeding therefrom, the smoke proceeding from a fresh supply of coal in the other chamber.

Sir W. Fairbairn thus comments on this invention:—'The principle of double furnaces within the same boiler was first introduced by myself. The two flues enable the stoker to fire alternately, and to maintain a more uniform generation of steam than with a single flue, and the flame, passing from one flue and mingling with the gases from the other, assists in their combustion. I believe that this simple system of alternate firing, when conjoined with the requisites of the economical generation of steam, viz., plenty of capacity in the boiler, sufficient admission of air, and, what is quite as necessary, careful and attentive stoking, will effect the prevention of smoke without any costly apparatus, so far as that is possible with any given description of fuel. Again, a double furnace tends to equalise the supply of air. The two furnaces, when fed alternately, will not require a maximum or

minimum quantity at the same time; and as the two currents of gaseous products mingle, the surplus air of the one furnace will supply the deficiencies of the other.'

143. The various modes in which fuel is wasted have been classified by Rankine somewhat as follows:—

1. Fuel is lost by the escape of gases in an unburnt state, or by permitting black smoke to be thrown off. Here the supply of air is defective, and the physical action is traced to the remarkable affinity of hydrogen for oxygen gas, whereby the oxygen is absorbed to the exclusion of carbon in the first instance.

2. There is waste from external radiation and conduction.

M. Peclet states that the quantity of heat radiated from incandescent charcoal, is ·5 of the total heat of combustion, and that the heat radiated from coal somewhat exceeds that radiated from charcoal.

The practical conclusion to be drawn from this statement is, that the heat radiated from the burning fuel should be carefully intercepted in every direction. Hence the economy resulting from the use of a Cornish or Lancashire boiler with internal furnace tubes.

As to the furnace door, that is in the form of a double plate, with perforations not coinciding, or there are plates set obliquely, like Venetian blinds.

As to the heat radiated into the ash-pit, that is carried back again to the fire by the current of entering air.

In respect of the loss of heat by conduction, that is obviated as much as possible by the use of firebrick, and where the furnace is outside the boiler the resistance to conduction is increased by double layers of brickwork, with enclosed air-spaces between the layers.

3. There is loss of heat by the escape of gases up the chimney at a temperature above that which is necessary for maintaining the draught.

A general idea of the value of a chimney in promoting the draught of a fire may be gathered from a statement of a law which appears to be approximately true, viz., that the velocity of air, as due to increased pressure, is that acquired in falling down a height equal to the uniform column which gives the increased

pressure. In making any calculations on this subject it is usual to adopt the hypothesis that air is incompressible and behaves as a liquid.

Let the increase of pressure support 5 inches of water. We know that $29{\cdot}922 \times 13{\cdot}596$ inches of water balance the pressure of the atmosphere which would be produced by a stratum of incompressible air 26,214 feet high. Therefore, 1 inch of water will balance 64·4 feet of air. Hence 5 inches of water balance 322 feet of air; therefore velocity due to increase of pressure

$$= \sqrt{64{\cdot}4 \times 322}$$
$$= 64{\cdot}4 \sqrt{5}$$
$$= 144 \text{ feet per second very nearly.}$$

According to the old rule the area of the chimney should be $\frac{1}{10}$ that of the fire-grate, and there should be 1 square foot of fire-grate for each horse-power. The consumption of coals per horse-power being estimated, Mr. Bourne gives Boulton and Watt's rule for proportioning the dimensions of land chimneys, according to which a factory chimney 80 feet high would have a sectional area of 400 square inches, the consumption of coal being 300 lbs. per hour, and the suction of the chimney being that due to a pressure of a little more than 1 inch of water.

Rankine gives formulæ for computing the height of a chimney in order to produce a given draught, and states that the best chimney draught takes place when the absolute temperature of the gas in the chimney is to that of the external air as 25 to 12, or when the density of the hot gas is one-half that of the external air.

For example, if the temperature of the external air be 50° F., the best temperature of the hot gas in the chimney will, according to this rule, be 602° F., which is less than that of melting lead, viz., 620° F. Hence the rule, that to insure the best possible draught in a chimney the temperature of the hot gas should be nearly sufficient to melt lead.

If the temperature of the furnace itself be estimated at 2,400 F., and that of the issuing gases at from 600° F. to 700° F., or even higher, as is often the case, we see that 25 per cent. of the heat of combustion passes up the chimney and is consumed in producing a draught of air through the furnace grate. The loss of heat from

the waste gases may be lessened by the use of an 'economiser' for heating the feed-water. Thus, in the case of some quadruple engines by Mr. Adamson, described in Chapter VII., the steam is supplied by two boilers, each 30 feet long by 7 feet diameter. The temperature of the injection-water is set down at 80° F., that of the feed-water from the condenser is 114° F., after which it passes through an economiser in the flue, consisting of 192 upright pipes each 10 feet long and 4 inches in diameter, where the temperature is raised as high as 262° F.; the temperature of steam in the boilers being 344° F.

Sir W. Fairbairn, in his treatise on 'Mills and Millwork,' p. 277, describes an economiser introduced by Mr. Green, of Wakefield, as consisting of a series of upright tubes forming a supplementary boiler placed in the main flues, and states that the 'formation of soot on the pipes was the source of the ill success of previous attempts in this direction. This difficulty has been overcome by an apparatus of scrapers or cleaners;' and it is found 'that when the waste gases escape at a temperature of 400° F. or 500° F. the feed-water can be heated to an average of 225° F., the temperature of the gases after leaving the pipes being reduced to 250° F. To produce this effect 10 square feet of heating surface should be provided for each horse-power.'

4. Fuel is wasted by brittleness, dust and small pieces dropping unburnt through the bars into the ashpit.

5. The fuel is rendered less effective by the presence of earthy compounds, which form clinkers, abstract heat uselessly, and choke up the grate.

THE LOCOMOTIVE BOILER.

144. In the Museum of the Patent Office there are placed, adjoining each other, two historical locomotive engines which show the form in which our present system of railway travelling was originated.

The first is the so-called 'Puffing Billy,' bearing the following label: 'This is the oldest locomotive engine in existence, and the first which ran with a smooth wheel upon a smooth rail. It was constructed, under Mr. Hedley's patent (A.D. 1813, No. 3,666),

for C. Blackett, Esq., the proprietor of the Wylam Colliery, near Newcastle-upon-Tyne. After many trials and alterations it commenced regular working in 1813, and was kept in use until June 6, 1872, when it was purchased for the Patent Museum.'

The second is Stephenson's 'Rocket,' being the engine which competed for and gained a prize of 500*l.* offered in 1829 by the directors of the Liverpool and Manchester Railway Company for the best locomotive engine which should draw three times its own weight upon a level road at the rate of ten miles per hour.

Mr. N. Wood, in his treatise on railroads, speaks of the improvements made upon locomotive engines before 1829, and shows their gradual development into the most perfect specimen which existed prior to Stephenson's invention, viz., the engine in use on the Killingworth Railway. He states 'that the locomotion of these engines was effected by the action of the wheels upon the rail, without the aid of any extraneous mechanism, and consisted of the hold or adhesion of the surface of the wheels against the surface of the rail.'

The boiler of the Killingworth engine was of malleable iron, cylindrical, with spherical ends of large radius. It was 9 feet long, 4 feet in diameter, with a cylindrical internal tube 2 feet in diameter passing through the boiler at a distance of 2 inches from the bottom, and terminating in the chimney, the firegrate being within the tube. In Mr. Blackett's engine the tube was carried round and brought back to the firegrate end, alongside of which was the chimney.

In applying the steam-engine to the purposes of locomotion the steam is of necessity used at a high pressure, and escapes into the external air after doing its work in the cylinder. The consumption of steam is therefore enormous, and the student should scrutinise minutely the progress made in solving the problem of generating a sufficient supply of steam within the limited space occupied by the boiler and firegrate.

It is stated that the heating surface in the old Killingworth boiler was 29·75 sq. feet, and that the engine evaporated 16 cubic feet of water in an hour, the average speed of the train being six miles per hour, and the weight of the load 50 tons.

The engines attached to the early locomotive were very rough

in construction. There were two steam cylinders, placed vertically and usually partly within the boiler. The pistons worked cranks respectively at right angles, and the engine ran upon four smooth wheels, with flanges on the inside, the naves and spokes being made of cast iron. In the Killingworth engine the wheels were 4 feet in diameter, and were coupled together, the boiler resting on a square frame of wood supported by springs, two on each side. It would be interesting to show the exact mode in which the power was communicated from the engine to the driving wheels in each early type of engine, but an explanation could not be given clearly without drawings (for which there is not space), and for information on this point we must refer to other technical treatises.

Although at the present day we may regard almost with a smile the early engravings of a line of railway with the stone sleepers, the fish-bellied rails, and the imperfect methods of connecting the different lengths, so as to make a continuous road, yet the whole invention is pretty clearly to be seen as far as the railway is concerned, and but little improvement is required in order to bring it up to modern ideas. As regards the boiler and engine the case is different, for the interval bridged over between the Killingworth engine and the Rocket was very great, and there was apparently nothing to lead from the one to the other.

It is dangerous to enter too closely upon the claims of inventors, and, according to a French writer, the tubular boiler was originated by M. Seguin, of the Lyons Railway, who patented his invention in France in 1828, and altered two boilers sent over by Stephenson in 1829. Also the height of the chimney being incompetent to maintain the draught through the tube, a circular fan was added, but this was found less effective than M. Pelletan's plan of discharging the waste steam into the chimney. The writer goes on to remark that the problem was thus fully solved, 'and, as usual, England appropriated the invention of the two French engineers.'

As to the steam-jet, that had been directed into the chimney of a Killingworth engine by Stephenson in 1825; but the chimney was large, and Mr. Wood considered that although it promoted evaporation it wasted fuel.

It has been mentioned that a prize was offered in 1829 for the

best locomotive engine. The trial was to take place on a 1½ mile course, with ⅛ mile extra at each end for starting and stopping. Twenty double trips were to be made.

Three engines were entered:—

1. The Rocket, by R. Stephenson, of Newcastle.
2. The Sanspareil, by T. Hackworth, of Shildon.
3. The Novelty, by Braithwaite and Ericsson, of London.

The Rocket had a cylindrical boiler, with flat ends, 6 feet long, and 3 feet 4 inches in diameter. The fire-box in the rear of the engine was 2 feet long, 3 feet broad, and 3 feet deep, inside measure, and was surrounded by a 3-inch water space. The flue consisted of 25 tubes, 3 inches in diameter, which are stated to have been adopted at the suggestion of Mr. Booth. The cylinders were two in number, placed obliquely next the fire-box, and working the fore wheels; they were 8 inches in diameter and 16½ inches stroke. The driving wheels were 4 feet 8 inches in diameter. It was originally intended that the exhaust should be directed into the open air, but the night before the trial an alteration was made, and the waste steam pipe was directed into the funnel. The fire-box surface was 20 feet, and the tube surface 117·8 feet. The engine, with its tender, weighed 7½ tons. For the above statements Mr. D. K. Clark is our authority.

The Sanspareil had a cylindrical boiler, 6 feet long and 4 feet 2 inches in diameter. Within the boiler was a horseshoe flue, containing the firegrate. The cylinders were vertical, and the wheels were coupled.

The Novelty had an internal flue traversing the boiler three times, and the fire was urged by a bellows.

At the trial the Rocket was victorious, being the only engine that ran the stipulated 70 miles. The average speed was 13·8 miles per hour, the greatest speed being 29 miles per hour. Coke consumed, ·91 lb. per ton of load.

The Sanspareil ran at an average of 14 miles per hour, the greatest speed being 22½ miles. Coke consumed, 2·41 lbs. per ton of load.

The Novelty broke down.

After the trial the orifice of the exhaust tube of the Rocket was contracted, to sharpen the blast and promote the generation of

steam. The amount of water evaporated was then 29·6 cubic feet per hour. The number of tubes was soon increased, till it reached, say 170, instead of 25, the amount of heating surface being raised so that the comparative numbers became roughly:—

Killingworth engine,	heating	surface,	30	square feet.
Rocket engine,	"	"	118	"
Narrow gauge engine,	"	"	1,000	"

The amount of water evaporated rising to some 100 cubic feet per hour.

The annexed drawing is copied from a lecture diagram, and may serve to give a general idea of the locomotive boiler as it was constructed some years after Stephenson's invention. The fire-box is at one end, marked A F, the firebars being at F. This box, for

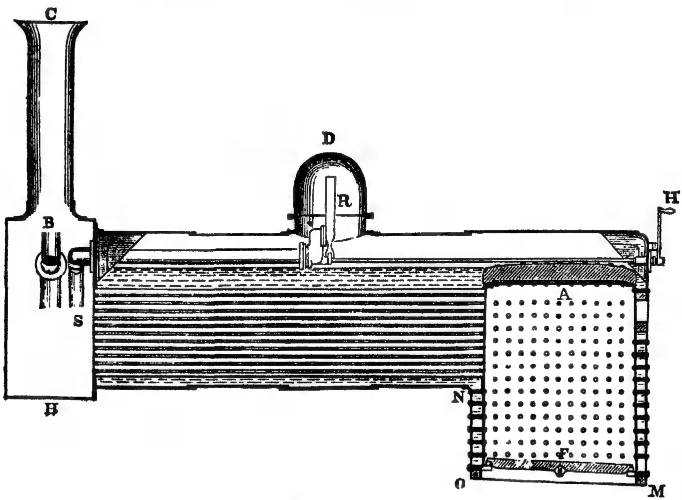


FIG. 112.

holding the fuel, is generally made of copper, on account of the superior conducting power of that metal for heat. Dr. Tyndall describes a good lecture experiment for showing that copper is a better conductor of heat than iron. A thermo-electric pile, connected with a galvanometer, is laid on a table with its face upwards, and upon it is placed a cylinder of copper, 2 inches long,

with flat ends, and just large enough to cover the whole face of the pile. A small block of iron, taken from a vessel of boiling water, is placed on the copper, and as soon as the heat has travelled through the metal and reaches the pile the needle of the galvanometer swings round to its stops.

The cylinder of copper is then replaced by another of iron, of exactly the same dimensions, and the experiment is repeated with an iron cylinder in the place of that of copper. It is found that a much longer interval of time, perhaps five or six times as great, elapses before the needle moves; and such a result might have been anticipated from an inspection of a table of conductivities of the metal, from which it appears that the conducting power of copper is to that of iron as 74 to 12. The rate at which heat travels throngh the metal depends, however, upon its specific heat as well as its conducting power, and therefore an illustration of this kind only affords a general confirmation of a physical fact, and is not in itself sufficient, although it may leave no doubt as to the superior conducting power of copper when compared with iron.

The fire-box of a locomotive boiler is surrounded with a casing of wrought iron, united to it by a number of copper bolts or stays, and leaving an interval for a water space, which serves the double purpose of keeping a quantity of water in immediate contact with the copper sides of the box and of supplying a ready and efficient mode of securing those sides from any injury due to the effect of steam pressure.

To the fire-box, and arching over the top of it, is attached the cylindrical barrel of the boiler, containing a large number of tubes leading directly from the furnace to the smoke-box B H. The number of such tubes has increased from 25 in the Rocket to 182 in the present example, each tube being about 10 feet long, 2 inches in diameter, and $2\frac{5}{8}$ inches from centre to centre. It may be estimated roughly that the heating surface of the fire-box and tubes amounts to 1,100 square feet.

The supply of steam is admitted to the engine by moving the handle H, which opens a *regulator* valve, as it is termed, situated in the steam-dome D, and allows a supply of steam to pass down the pipe marked S and so into the cylinders. After the steam has done

its work it is discharged by the pipe B, which is placed directly under the centre of the chimney, and drives out the air before it so as to increase prodigiously the draught through the tubes.

145. In order to heighten the effect thus produced by the action of the waste steam, upon which the success of the locomotive boiler mainly depends, the blast pipe is contracted somewhat at the orifice, so as to spread the jet of issuing steam and make it act as if it were a solid piston driving the air before it through the chimney. On comparing the action of this steam-pump with that of the lofty chimney of a stationary boiler the result is certainly remarkable. Applying a siphon water gauge to test the performance of a chimney on a prodigious scale, as in the gas-works at Edinburgh, where the stack is 340 feet high, 20 feet inside diameter at the bottom, and $11\frac{1}{3}$ feet inside diameter at the top, and where the gases from 68 furnaces heating retorts are being collected and passed into the atmosphere, it is recorded that the vacuum on a calm day was about $2\frac{1}{2}$ inches, whereas in windy weather it rose to $3\frac{1}{2}$ inches, and amounted under high winds to as much as 6 or 7 inches. The increase here noticed was clearly due to the influence of a cross-draught at the top of the chimney.

Taking the greatest pressure of the wind in England at $32\frac{1}{2}$ lbs. per square foot, and that of atmosphere as 2116·4 lbs. per square foot, or 65 times as great, we infer that the pressure of the strongest gale would raise water in the leg of a siphon gauge through $\frac{33}{65}$ feet, or 6 inches, and these numbers will give some insight into the pressure of the wind as compared with the artificial draught of a chimney. At any rate they assist us in estimating what takes place under the blast of the locomotive, when we are told, as by Mr. D. K. Clark, that in a locomotive engine where the boiler had 148 tubes, with a blast orifice $3\frac{7}{8}$ inches in diameter, the vacuum in the smoke-box at a speed of 16 miles per hour was $1\frac{7}{8}$ inches, as shown by a siphon gauge, whereas at 20 miles per hour it improved to $2\frac{7}{8}$ inches, and at 30 miles per hour to $4\frac{1}{4}$ inches; the recorded vacuum in another engine running at 40 miles per hour being $6\frac{1}{2}$ inches, or about equal to that, under exceptional circumstances, with a chimney 340 feet high. Mr. Clark analyses, in a very useful dissertation, the various conditions which modify or vary the exhausting power of the blast, from

which it appears that every part of the locomotive boiler has been subjected to careful experiment, in order that the best result may be obtained.

Some idea of the dimensions of the various parts should be given; and, taking the case of a passenger engine by R. Stephenson and Co. for the South-Eastern Railway, as described by Mr. Clark in 1860, we find that the fire-box is 4 feet long, 3½ feet wide, and 5⅓ feet deep, surrounded by a water space 2½ inches across. In an ordinary furnace of a stationary boiler the layer of fuel is some 4 inches deep, whereas here it might be as much as 1½ feet deep, or even more, and the different conditions for burning the fuel are apparent at once from this statement.

For a modern example we refer to an express engine on the London and North-Western Railway, where the cylinders are inside, between the frames—in the smoke-box, in fact—and have a diameter of 17 inches, with a stroke of 24 inches. The area of the fire-grate is 15 square feet, the heating surface of the fire-box being 89 square feet, and that of the tubes 1,013 square feet. The boiler is fed by two injectors placed vertically behind the fire-box. The distribution of weight on the wheels is stated to be 9 tons 9 cwt. on the leading axle, 11 tons on the driving axle, and 8 tons 15 cwt. on the trailing axle. The total wheel base is 15 feet 8 in. The engine can draw a load of 293 tons on a level at a speed of 45 miles per hour with a working pressure of 120 lbs. per square inch. There are four driving wheels, each 6 ft. 7½ in. in diameter, coupled together by outside rods, the leading wheels being 3 ft 7½ inches in diameter. The consumption of coal per mile is 26·3 lbs. with trains averaging ten carriages.

Also for burning coal instead of coke there is a brick arch over the fire-box extending from the front backwards through half its length. Under this arch are two circular 7-inch holes covered by doors which are worked from the foot plate and regulate the supply of air.

146. There is not space to discuss fully the question of the strength of the various parts of the locomotive boiler. It is obvious that the rules as to the strength of the cylindrical barrel calculated for the Lancashire boiler apply equally here, and in regard to the fire-box we have only to point out that where one flat side is in

juxtaposition with an outside flat casing, and connected with it by stays, there is abundance of strength, as due to the stays—two flat surfaces held together by a number of intermediate stays, and subjected to equal pressures in opposite directions, being a construction which presents no difficulties. But the same cannot be said of the flat crown or roof of the fire-box, above which, at a little distance, is the arched top of the cylindrical barrel. A method adopted on the Great Northern express engines is to connect the roof of the fire-box to the external shell by wrought iron radiating stays, each $\frac{7}{8}$ inch in diameter, screwed into the copper plates and into the iron casing. Another method is that indicated in fig. 112, where a series of ribs or girder beams are fitted to the bends of the front and back plates of the firebox, and to them the flat roof is bolted. The ribs are further linked to the crown, so as to take part of the downward strain on the lateral fixings of the fire-box.

THE MARINE BOILER.

147. We pass on to the marine boiler of the old-fashioned type, which originally was provided with flues, but now has tubes, and which possesses an advantage at one time seriously referred to, viz., that it can be adapted to the shape of the boat (see page 94). The general construction will be apparent from the sketch without any particular description. The furnace is enclosed entirely within the shell, and the hot gases pass through a series of horizontal tubes, which are larger in diameter than those in a locomotive boiler (say from 3 to 4 inches in diameter). After passing through the tubes the gases enter a smoke-box corresponding to that previously described and rise by the uptake into the funnel.

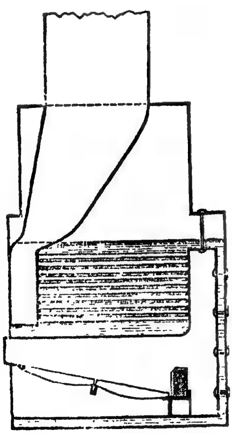


FIG. 113.

As the sketch shows only a section of a boiler which is really in the form of a box, a very little alteration would make it serve to represent a

marine boiler for generating steam under a high-pressure. Such a boiler may consist of a cylinder some 10 feet long and 12 feet in diameter, the section of which is very similar to that shown, the ends being flat, and a series of tubes running horizontally through the water space above the fire. It is unfortunate that the limits of this book do not permit of a more extended reference to this branch of engineering construction.

PROPORTION OF FIRE-GRATE TO HEATING SURFACE.

148. Before concluding the chapter something should be said as to the relation between the area of the fire-grate and the amount of heating surface in the boiler itself. This is a practical question which has been settled to some extent by experience, and the result can only be stated on authority.

In the Lancashire boiler, 27 feet long, with two internal flues, the fire-grate has an area of about 33 sq. feet, and the heating surface in the shell, furnace tubes, and water pipes amounts in all to about 850 sq. feet; whence the proportion of fire-grate to heating surface is about

1 to 26.

Sir W. Fairbairn states ('Mills and Millwork,' p. 267) that he has usually adopted the proportion of 1 to 17; that the allowance in Cornish boilers is about 1 to 25, whereas it has been a practice in stationary boilers to adopt the ratio of 1 to 10 or 15.

In the North-Western express engine above referred to the fire-grate area is 15 sq. feet, and the heating surface is 1,102 sq. feet, making the ratio of fire-grate to heating surface as 1 to 73, while in a goods engine for an Indian railway the heating surface is 1,327·3 sq. feet, and the area of the fire-grate is 25·5 sq. feet, making the ratio 1 to 52. In a marine boiler generating steam at 80 lbs. pressure the heating surface may be 3,100 sq. feet, and the area of the fire-grate 117 sq. feet, making the above proportion about 1 to 26.

CHAPTER VII.

COMPOUND CYLINDER ENGINES.

149. It has been stated that an engine with two steam cylinders, one exhausting into the other, was invented by Hornblower, in the form of a single-acting engine, and that it was converted by Woolf into a double-acting engine.

In 1804 Woolf took out a patent (No. 2,772) for 'certain improvements in the construction of steam-engines,' in which he proposed to employ two steam cylinders of different dimensions, each furnished with a piston, the smaller cylinder having a communication at the top and bottom with the boiler, but communicating also with the two ends of the larger cylinder in suchwise that the steam should cause both pistons to rise and fall together.

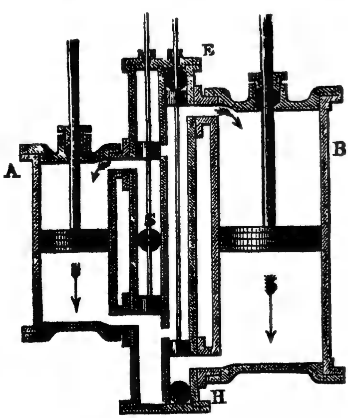


Fig. 114.

The specification describes the admission of steam at a pressure of 40 lbs. on the square inch into the smaller cylinder, so as to drive the piston down at the time that steam from below the same piston is expanding into the larger cylinder, and pressing its piston also in the same direction.

The working of such an engine will be understood from the sketch (taken from a lecture diagram), where the valves are small pistons moving in cylindrical passages. Steam is entering at S, and passes at once to the upper end of the cylinder A, while

the steam below the piston in A is escaping by an open passage to the upper part of the large cylinder B. At the same time the steam below the piston in B is escaping into the pipe H, which leads to the condenser. Thus both pistons descend together.

On depressing each valve rod the passages are reversed. Steam from S enters the lower part of A, while steam from the upper portion of A passes down into the lower part of B. Also the upper end of B is freely in communication with E, which is also a passage leading to the condenser.

Hence the two pistons are similarly actuated by the joint pressure of the steam in each cylinder. Woolf was here adopting Hornblower's engine to a new purpose, and his specification is principally remarkable for a palpable error made in the statement of advantages to be derived from the use of high-pressure steam. Woolf says :—'I have ascertained by actual experiments, and have applied the same to practice, that steam acting with a pressure of 4 lbs. the sq. inch against the safety valve exposed to the atmosphere is capable of expanding itself to *four* times the volume it then occupies, and still be equal to the pressure of the atmosphere.' And the like for steam of 20 lbs., 30 lbs., 40 lbs. the sq. inch on the safety valve when expanding to twenty, thirty, forty times its original volume, the resulting pressure would 'be that of the atmosphere.' Thus steam of 20+15 lbs. actual pressure would expand twenty times in reducing its pressure to 15 lbs.

Although Woolf wandered thus hopelessly in his theories he was a thoroughly practical mechanic, and performed most admirable work in the construction of high-pressure engines, and in advocating tubular boilers for the generation of high-pressure steam.

ENGINES OF SIMS AND M^CNAUGHT.

150. In 1841 a patent (No. 8,942) was taken out by J. Sims for a compound cylinder engine, the improvement consisting 'in constructing a steam cylinder divided into two parts of different areas, and with two pistons attached to one rod, whereof one fitted the upper and the other the lower part of the said cylinder.'

A constant vacuum was maintained in the space B B between

the two pistons by the open pipe T leading into the condenser, and a pipe H, provided with an equilibrium valve E, formed a communication between A and C. The specification described the area of P as being one-fourth that of R, and steam from the boiler was admitted into A, through the valve S, during a portion (say one-third) of the down stroke, and the space C was opened to the exhaust, whereby P descended, as in any ordinary engine. On the return stroke E was opened, when the pressures in the spaces A and C became equal; and since the area of P was much less than that of R, the pressure in C would preponderate and P would be carried upwards. The arrangement of the valves bore a close resemblance to that in a single-acting engine, and the peculiarity consisted in the preservation of a constant vacuum between the pistons. As far as expansion was concerned, a portion of the down stroke and the whole of the up stroke was performed after the cut-off had taken place.

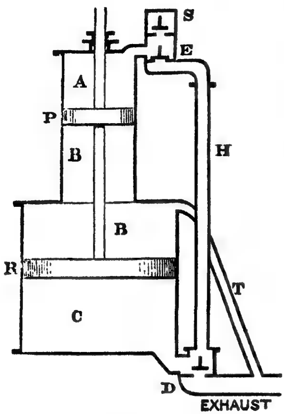


FIG. 115.

151. In 1845 W. McNaught patented (No. 11,001) a new form of engine, wherein a high-pressure cylinder was incorporated in an ordinary condensing engine of the overhead beam construction. This process, whereby many old and wasteful condensing engines were converted into useful compound cylinder engines, was called *McNaughting* an engine. The patentee described the improvement to consist in the application of a non-condensing cylinder to the kind or description of condensing or low-pressure beam engines commonly used, and attaching the high-pressure cylinder to the working beam at the end opposite to that with which the low pressure cylinder is connected, whereby the steam, after being used in the usual way in the non-condensing cylinder, passed into the nozzle of the condensing cylinder, and was there used for impelling its piston, after which it escaped into the condenser.

The specification contains a drawing of the compound engine, and describes a method of deriving the valve motion of each cylinder from one and the same eccentric.

DOUBLE CYLINDER PUMPING ENGINES.

152. An example of double cylinder engines which has been regarded with much interest is to be found in the pumping engines erected by Messrs. Simpson at the Lambeth waterworks, where four engines of 150 H.P. each are fixed side by side, arranged in two pairs, each pair working into one shaft, with cranks at right angles, and a flywheel between them. The stroke of the crank is equal to that of the large cylinder, but the small cylinder, which receives steam direct from the boiler, has a shorter stroke, and its effective capacity is nearly one-fourth that of the large cylinder. The pumps are of the combined plunger and bucket construction, that is to say, they are double-acting and have only two valves. They are connected with the beam near its end. One peculiarity of these engines consists in the use of a crank and fly-wheel for controlling the motion of the piston. The work to be done was that of forcing water along a cast-iron main, 9 miles long and 30 inches in diameter. As stated by Mr. Pole, in his account of the matter, 'the great mass of water in motion along the main, combined with the fragile nature of cast-iron, rendered it essential that the motion should go on in the most equable manner, and that concussions or irregularities of pressure should be as much as possible avoided.' The inequality in the action of a single cylinder pumping engine was therefore dreaded, and Mr. Pole, in conjunction with Mr. D. Thomson, was led to design engines connected with a fly-wheel and at the same time admitting a high degree of expansion in the use of steam. The fly-wheel ensured regularity of motion, and the pair of cylinders gave an opportunity of increasing the ordinary rate of expansion.

The engines were on a large scale, the low-pressure cylinder being 46 inches in diameter, with 8 feet stroke, and the high-pressure cylinder being 28 inches in diameter, with a stroke of 5 feet $6\frac{3}{8}$ inches. The length of the beam was $26\frac{1}{2}$ feet. Also the stroke of the pump was 7 feet, the diameter of the pump barrel being about 23 inches.

153. The valves were arranged so as to prevent as far as possible any loss of pressure in the passage of steam from the high to the low pressure cylinder. The general character of the valve for distributing steam is apparent from the diagram, which does not indicate in any way the details of construction. It will have been noticed that in the sketch of Woolf's engine two double piston valves are caused to work in distinct passages. Here, however, a single valve fulfils the same office as the pair of valves in the former case, and the idea appears to have been to place two of Murdock's valves back to back and mould them into a single hollow but closed pipe, with ports at its two ends.

154. The drawing shows the high and low pressure cylinders, marked respectively A and B, and placed side by side with the

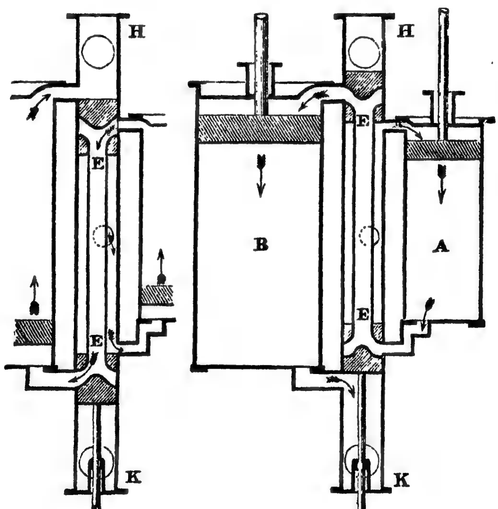


FIG. 116.

valve E E, working in a pipe H K lying between the steam cylinders. The circles at H and K represent passages leading to the condenser, steam being admitted into the middle of the slide case by a pipe marked on the sketch. In the right-hand figure steam is supposed to be entering above the piston in A and driving it downwards,

while steam from below the same piston is passing up the pipe E E and entering the space above the piston in the low-pressure cylinder B. At the same time steam below the piston in B is escaping through an open port into the passage K leading to the condenser. Thus the pistons descend together, and may therefore be attached on the same side of the fulcrum of a working beam.

In the left-hand figure the pistons are both represented as scending after the completion of the downward stroke. Steam is entering below the piston of the high-pressure cylinder, and a clear passage is open from the top of the same cylinder down the pipe E E and into the space below the piston in the low-pressure cylinder. At the same time the top of the larger cylinder is freely open to the exhaust pipe H. Thus both pistons ascend together, the steam from A exhausting into B, while B itself has one end open to the condenser. The action is extremely simple, and will be readily understood.

The valves, which are worked by cams, are cylindrical, and are packed by cast-iron rings, as in the case of an ordinary piston, springs being placed inside the rings, in order to assist their elasticity in pressing outwards and ensuring that the surfaces of contact shall be steam-tight. The cylinder ports are rectangular, with inclined bars across the faces, to prevent the packing rings of the valves from catching against the edges of the ports.

It is stated that the passage E E is 6 inches in diameter or one-sixtieth of the area of a section of the low-pressure cylinder, the speed of the piston thereof being 230 feet per minute. It appears that the valve has completely answered the expectation formed of it in permitting only a very moderate fall of steam pressure during the passage from A to B.

155. The drawing on the next page shows the arrangement of a compound cylinder beam engine of moderate size. The sketch has been simplified by substituting dark lines for many of the working parts. In particular the student will find the parallel motion set out in that manner, and he should refer back to p. 122 for fuller explanation. There are two black spots on the circular space representing the end of the crank shaft, the object being to indicate the centres of the eccentric sheaves which work the valves. Also dotted lines pass from these points to other dark spots just

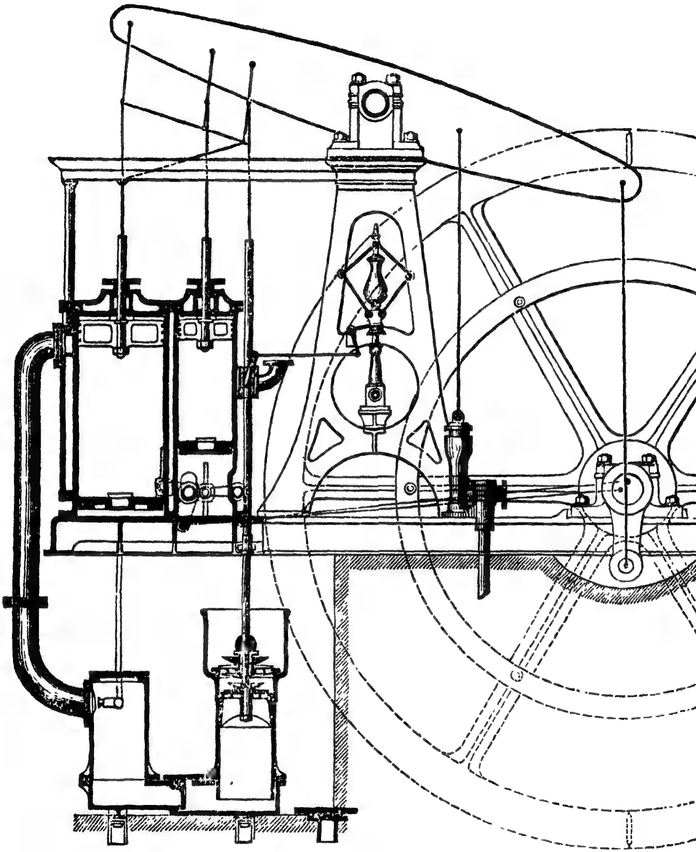


FIG. 117.

under the base of the high-pressure cylinder, and are intended to show the connection from the eccentrics to the bell cranks working the valves. The governor is clearly indicated, and the reason for its particular form will be discussscd hereafter. At present we may point also to the section of the condenser and air pump, the

bucket being fitted with indiarubber valves, as subsequently described.

The dimensions of the engine are the following:—

Diameter of high-pressure cylinder . .	$12\frac{1}{2}$ inches.
Length of stroke	2 feet.
Diameter of low-pressure cylinder . .	20 inches.
Length of stroke	3 feet.

156. The general character of the indicator diagram taken from Mr. Pole's double cylinder engine will be understood from its analogy to the diagram from a single-acting engine.

1. As to the high-pressure cylinder, that appears to monopolise the greater part of the area of work done, but it must be borne in mind that the diameter of the piston in A is much less than that in B, and also that, in the case of a beam engine, the length of stroke is less. Hence the upper diagram requires to be viewed on a diminished scale before it can be fairly compared with the lower one.

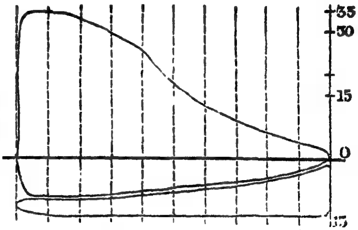


FIG. 118.

2. As to the low-pressure cylinder, that gives the diagram of an ordinary condensing engine, and no remark is necessary with regard to it, except that the space of separation between the two figures is seldom so small as in the present example. There is commonly a much more considerable loss of pressure in passing the steam from the high to the low pressure cylinder than that shown by the divergence of the exhaust and steam lines in the middle portion of the diagram.

According to the present illustration steam is admitted into the small cylinder at 35 lbs. pressure, and is cut off at four-tenths of the stroke, the total expansion being carried on in the large cylinder until it reaches eight times. Here, then, is an example of a compound cylinder condensing engine working at a steam pressure of 35 lbs. above the atmosphere and expanding eight times, but yet preserving the smoothness and uniformity of motion appertaining to an ordinary condensing engine expanding at a low rate, as in the early days of steam power.

In one trial of these engines the recorded duty for 112 lbs. of coal was 97,064,894 ft.-lbs., which is equivalent to 2·3 lbs. of coal per actual H.P. per hour, neglecting friction and other losses.

CALCULATION OF WORK DONE IN A COMPOUND CYLINDER ENGINE.

157. In the working of a compound cylinder engine, where the small cylinder exhausts into the large one, the work done in a stroke depends on the size of the large cylinder, and is the same as that which would be performed in a single cylinder of the same content, by expanding to the same extent from a like initial pressure.

This proposition is easily proved, and anyone may satisfy himself that it is approximately true by examining a well-formed indicator diagram as taken from a compound cylinder engine.

Referring to fig. 119, which is from an engine having a high-pressure cylinder 18 inches in diameter, with a 6-feet stroke, and a low-pressure cylinder 36 inches in diameter, with a stroke also of 6 feet, the number of revolutions being 34 per minute :

Since the lengths of stroke are the same, and the areas of the pistons are as 1 to 4, it follows that the indicator diagram, marked A, as taken from the high-pressure cylinder, would be reduced to the same scale as that from the low-pressure cylinder, marked B, if we supposed the diameter of the latter cylinder to be 36 inches and the stroke $\frac{6}{4}$ feet, or one-fourth of that which it really is. This result is set out in the sketch. The diagram marked A is reversed in position and repeated on the right-hand side by measuring off a series of horizontal lines, such as C D, and making $c\,d = \frac{1}{4}$ C D in every case. In this way the upper shaded area represents the work done in the high-pressure cylinder as it would appear on the scale adopted in the low-pressure cylinder. The bottom shaded area is merely a repetition of the area B.

When the two diagrams are put together it will be seen that the two portions of the expansion curves fit very fairly or run into one, and that the expansion commenced above d is carried on throughout the stroke. It will be noticed that there is a little defect of similarity between this diagram and fig. 118. Here the

steam line in B is horizontal at first, and then slopes downwards. That it is horizontal at all is owing to some peculiarity in passing

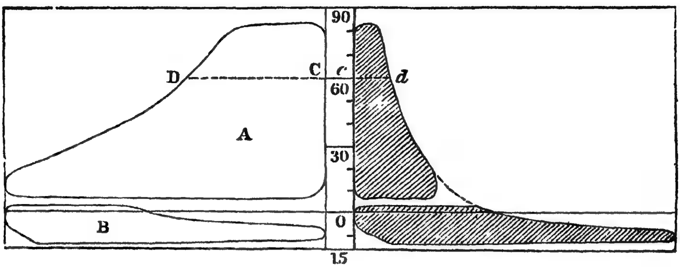


FIG. 119.

the steam from one cylinder to the other, as there should be the slope of an expansion curve throughout.

But any deviation from theoretical proportions does not affect the general inference to be drawn from the two diagrams when viewed together, and we see that the expansion which has occurred in the high-pressure cylinder might very well have taken place in the low-pressure cylinder, as something which preceded the actual expansion therein.

158. The mathematical proof is the following:—

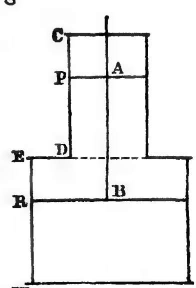


FIG. 120.

Since the bottom of the smaller cylinder opens into the top of the larger one, it will simplify matters to suppose the cylinders to be in one line, with their pistons at P and R such that CP = ER.

Let CD = EH = l, CP = ER = x.

Also let A and B be the areas of the smaller and larger pistons, the pressure of the steam above A being p, that below it being p', and that below B being zero.

Then $p' : p = l\text{A} : (l-x)\text{A} + \text{B}x$ (by Boyle's law).

$$\therefore p' = \frac{p\,l\text{A}}{l\text{A} + (\text{B}-\text{A})x}.$$

$$\therefore \text{ work done} = \int \text{A}\, p\, dx + \int p'\,(\text{B}-\text{A})\, dx$$

$$= \text{A}\, p\, x + \text{A}\, p\, l. \int \frac{(\text{B}-\text{A})\, dx}{l\,\text{A} + (\text{B}-\text{A})\, x}$$

$$= \text{A}\, p\, x + \text{A}\, p\, l \log. \{l\,\text{A} + (\text{B}-\text{A})\, x\} + \text{C}.$$

Taking the integral between the limits $x = l$, $x = 0$, we have

$$\text{work done} = \text{A}\, p\, l + \text{A}\, p\, l\, \{\log. \text{B}\, l - \log. \text{A}\, l\}$$

$$= \text{A}\, p\, l \left\{ 1 + \log. \frac{\text{B}}{\text{A}} \right\} \quad . \quad . \quad . \quad . \quad (1).$$

If the steam had expanded in a single cylinder of sectional area B, and the cut-off had occurred when the piston had traversed a space y, the expansion being finally in the ratio $\frac{\text{B}}{\text{A}}$, we should have had $y = \frac{\text{A}\, l}{\text{B}}$; and, applying the formula of Art. 112, it would be found that

$$\text{work done} = \text{B}\, p\, y \left\{ 1 + \log. \frac{\text{B}}{\text{A}} \right\} \quad . \quad . \quad (2).$$

But $\text{B}\, p\, y = \text{A}\, p\, l$, and therefore the expressions (1) and (2) are identical, which proves the proposition.

Cor. The form of equation (1) may be altered. Thus, let the steam expand E times, so that $\text{E} = \frac{\text{B}}{\text{A}}$,

$$\therefore \text{ work done} = \frac{\text{B}\, p\, l}{\text{E}} \left\{ 1 + \log. \text{E} \right\}.$$

So, also, equation (2) becomes, $\left(\text{since } y = \frac{l}{\text{E}}\right)$,

$$\text{work done} = \frac{\text{B}\, p\, l}{\text{E}} \left\{ 1 + \log. \text{E} \right\}.$$

POINT OF CUT-OFF IN SMALL CYLINDER.

159. Mr. Pole proved, in 1851, that in the case of expansion with compound cylinders there is one particular point of the stroke where the steam may be most advantageously cut off, so far as the initial pressure on the pistons is concerned, and that such pressure

may be reduced to a minimum value dependent on the degree of expansion. The investigation is the following :—

Let l represent the length of each cylinder,

r the length of stroke in the small cylinder before the cut-off.

A, B the areas of the pistons of the small and large cylinders respectively, B being constant, while A and r vary.

p the pressure of the steam on admission into the smaller cylinder, whence $\frac{p\,r}{l}$ is its pressure on admission into the large cylinder. Then

$$\text{initial pressure} = p\,\text{A} + (\text{B} - \text{A})\frac{p\,r}{l}.$$

$$\text{But the whole expansion} = \frac{\text{B}}{\text{A}} \times \frac{l}{r} = \text{E suppose.}$$

$$\text{Let } \frac{r}{l} = z, \text{ then we have } p\,\text{A} = \frac{p\,\text{B}}{\text{E}\,z}$$

$$\therefore \text{ initial pressure} = \frac{p\,\text{B}}{\text{E}\,z} + \text{B}\,p\,z - \frac{p\,\text{B}}{\text{E}} = \text{a minimum.}$$

$$\therefore 0 = -\frac{1}{\text{E}\,z^2} + 1,$$

$$\therefore z = \frac{1}{\sqrt{\text{E}}}$$

$$\text{or } l = r\sqrt{\text{E}}.$$

Which determines the point of cut-off when the initial pressure of the steam on the two pistons is the least possible.

$$\text{Also, initial pressure} = \frac{p\,\text{B}}{\text{E}\,z} + \text{B}\,p\,z - \frac{p\,\text{B}}{\text{E}},$$

$$= p\,\text{B}\left\{\frac{1}{\sqrt{\text{E}}} + \frac{1}{\sqrt{\text{E}}} - \frac{1}{\text{E}}\right\}$$

$$= p\,\text{B}\left(\frac{2\sqrt{\text{E}} - 1}{\text{E}}\right).$$

Ex. 1. Let $\text{E} = 10$, $\therefore\ r = \frac{l}{\sqrt{10}} = \frac{l}{10}\sqrt{10} = l\,(\cdot 32)$ nearly.

$$\text{Also } \text{A} = \frac{\text{B}}{\sqrt{\text{E}}} = \frac{\text{B}}{10}\sqrt{10} = \text{B}\,(\cdot 32) \text{ nearly.}$$

$$\text{Initial pressure} = p\,\text{B}\left(\frac{2\sqrt{10} - 1}{10}\right) = p\,\text{B} \times \cdot 532.$$

Ex. 2. Let $E = 8$, $\therefore r = \frac{l}{\sqrt{8}} = \frac{l}{2\sqrt{2}} = \frac{l\sqrt{2}}{4}$,

And $\sqrt{2} = \sqrt{\frac{50}{25}} = \frac{7}{5}$ nearly, $\therefore r = \frac{7l}{20} = \frac{35l}{100}$.

ENGINES WITH CRANKS AT RIGHT ANGLES.

160. For many purposes it is enough to have an engine with a single steam cylinder, or the equivalent Woolf's engine, with a pair of cylinders acting as one only; but, on the other hand, there are numerous instances where two engines should be placed side by side and work cranks at right angles to each other. This is particularly the case in applying steam-power to flour mills or to cotton mills, where it is of consequence to preserve the rotative pressure on the crank as nearly uniform as possible, and to maintain a smooth and even motion. Or, again, in marine engines, for convenience of starting in any position, the same rule would hold; and before proceeding further it may be useful to point out the reason for the greater uniformity of rotative pressure which is a consequence of working with a pair of cranks at right angles.

It has been shown in Art. 110 that the variations of tangential pressure on the crank of a direct-acting engine are represented by the vertical lines on a diagram similar to that shown by the dotted curve *b f* in the annexed sketch. Putting a series of such curves end to end, we obtain a graphical indication of the fluctuations of

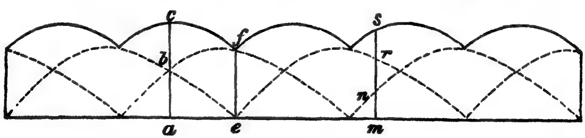


FIG. 121.

tangential pressure during the working of an engine with one cylinder. The force is zero at a dead point, and rises to *f e*, its greatest value, after which it sinks again to zero. But if there be a pair of cranks at right angles, a second series of diagrams of rotative pressures must be superposed upon the first series, as shown by the second set of dotted curves, whereof one portion is

marked $b\,e$, and the final result is exhibited by the upper line, not dotted, which is obtained by adding together the pairs of ordinates at each point; for example:—

$$nm + mr = ms,$$
$$ab + ab = ac,$$
$$ef + 0 = ef.$$

The greater uniformity of rotative force is apparent, and it would be improved by cutting off at half-stroke in each cylinder, for then the curve $b\,e$ would be hollowed out and reduced, while the part $b\,f$ would be unaffected, and the upper resultant wavy line would become more nearly horizontal. By proceeding in this manner it is easy to set out a diagram of the rotative pressure upon the cranks of any pair of engines working under given conditions.

161. In applying Hornblower's principle to direct-acting engines, where two cranks at right angles are to be connected with the cylinders, there are different methods for adoption, each of which has its advocates. One plan very commonly met with has been to place the high and low pressure cylinders in pairs, with their axes in the same straight line, so that one piston rod serves for both. Thus, in marine engines, with the cylinders vertical, there may be—

1. The high-pressure cylinder above the low-pressure cylinder.
2. The low-pressure cylinder at the top.
3. The low-pressure cylinder encasing the high-pressure cylinder.

But in each of these cases, as also in compound cylinder horizontal engines, it is usual to confine the expansion to one pair of cylinders, although there is an example, to which reference will shortly be made, in which the steam is carried in succession through four cylinders.

THE USE OF AN INTERMEDIATE RECEIVER.

162. In another class of compound cylinder engines there are two cranks at right angles, but only one cylinder connected with each crank. Here each cylinder forms, as it were, an engine complete in itself; the cylinders (called A and B, as before) are placed side by side, and are of equal length, and the point to be

noticed is, that the pistons in A and B no longer move together, but that one leads the other by half a stroke. It is clear that Hornblower's mode of exhausting at once from A into B is no longer applicable, and that some special method of distributing the steam, different from anything that we have yet seen, must be arranged. The difficulty arises from the fact that the directions of motion of the pistons cross each other, whereby, for example, when the piston in A is at the end of its stroke and about to ascend, that in B is in its middle position and is descending. In order to get over this obstacle Mr. Cowper has proposed to place an intermediate receiver between the cylinders A and B, which shall act as an exhaust reservoir for the steam coming from A, and as a boiler for the steam going into B. It appears that engines with a receiver have worked well in practice, but it seems difficult to justify the use of this arrangement by a strict reference to the principles of the theory of heat.

A general idea of the arrangement of the engine proposed by Mr. Cowper may be gathered from the sketch, where the cylinders

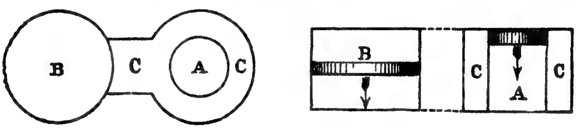


FIG. 122.

A and B are placed side by side, and the high-pressure cylinder A is enveloped in a steam receiver or reservoir, marked C, the content of which is perhaps three times that of A. In a working engine on this plan steam (say at 70 lbs. pressure) would enter A and be cut off at half-stroke; it would then expand and finally exhaust itself into the receiver, where the pressure would vary from, say, 10 lbs. to 14 lbs. The receiver would supply steam for the low-pressure cylinder B, just as if it were the boiler of an ordinary engine, and the pressure of the steam in C would fall to 10 lbs. when the demand upon it was made, but would rise to 14 lbs. when fresh steam entered it from A.

The temperature of the steam in the jacket surrounding A is, therefore, much below that of the entering steam, which is so far a departure from Watt's practice.

MILNER'S COMPOUND CYLINDER ENGINE.

163. A mode of working a compound cylinder engine with two cranks at right angles, and without an intermediate receiver, was patented by J. Milner in 1853, No. 2,281. It does not appear that the engine has ever come into use, but it is referred to as an exercise for the student.

The specification describes the engine as having two working cylinders, with pistons connected to two cranks placed at right angles to each other on the same shaft, one of the cylinders being of greater capacity than the other. The valves are worked by cams or eccentrics, and it is 'arranged that steam may be admitted from a boiler into the top of the smaller cylinder until the piston has made half its stroke, and then be shut off. A communication is next made between the top of the first cylinder and the top of the second one, whose piston is then at the top of its stroke.'

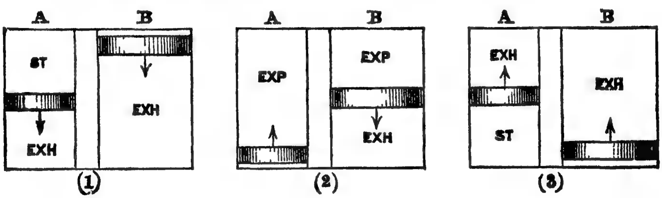


FIG. 123.

The part of the sketch marked (1) shows the piston of the smaller cylinder A descending, the steam being just shut off, while the piston in the larger cylinder B is at the top of its stroke, and is on the point of descending, as marked by the arrow.

As to the opening of the cylinders A and B to the condenser, it is to be observed that the lower part of A is open to the exhaust during one half of the down stroke, and the same is true of the upper part of A during one-half of the up stroke; whereas the two ends of B are alternately open to the exhaust through nearly a whole stroke, just as in an ordinary engine.

The distribution of steam is different from that in the compound engines hitherto examined. The steam which passes from

A to B is not conducted from the top of A to the bottom of B, and so on, but the direct contrary, whereby the method which appears most natural, and which was originated by Hornblower, is abandoned. Steam passes from the top of A to the top of B and expands against both pistons at the same instant.

Diagram (2) shows this expansion going on. There are two ordinary D valves working against steam-ports connected with A, one at the top and the other at the bottom thereof, and the exhaust passages communicate from the top of A to the top of B, and from the bottom of A to the bottom of B.

Diagram (3) shows the state of things when the piston in B has come to the end of its stroke and is beginning to return, the upper ends of A and B having been just opened to the exhaust. And it is apparent that during the interval existing between (2) and (3) the space occupied by steam is getting less in A and is becoming larger in B, whereby the actual expansion is from $\frac{A}{2}$ to $B + \frac{A}{2}$, that is, from A to A + 2 B.

There is no difficulty in seeing that the action which is now beginning in (3) would pass through a like phase to that indicated in (2), and that expansion will go on between the lower ends of A and B until the piston in B has reached the top of its stroke, when openings to the exhaust will be made in both cylinders, as shown by diagram (1). After this the operation repeats itself.

The indicator diagram, which might be taken from the high-pressure cylinder of a Milner's engine, is the only one which presents any peculiarity, and would be somewhat of the character sketched. The actual expansion between A and B begins at half-stroke in A, but there may be a preliminary cut-off of the steam in A, as shown at *a*, and in such a case the expansion would be carried a little farther than has hitherto been supposed. The steam in A begins to expand into the cylinder B at the point *b*, and this goes on until half the return stroke is completed, when there is a sudden opening to the exhaust. This causes the pressure to drop, and there is the lowering, marked at *d*, which indicates the gain

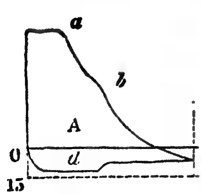


FIG. 124.

due to this mode of working. The diagram in the other cylinder—viz., B—is the same as in the case of any ordinary double cylinder engine.

QUADRUPLE ACTION ENGINE.

164. We have now to mention a successful engine by Mr. Adamson, where the expansion is carried on through four cylinders, A, B, C, D, whereof A and B are in one line, and have a common piston rod, as are also C and D, the two cranks on the driving shaft being at right angles, and the general arrangement of the engine being that shown in the sketch.

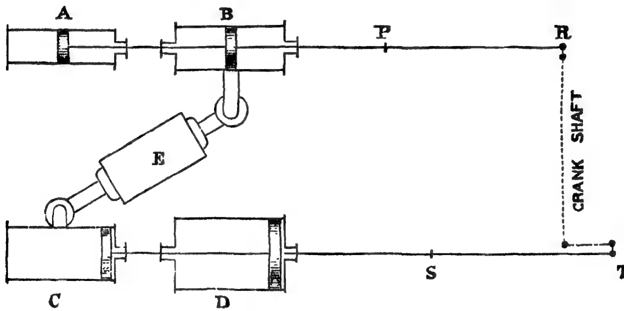


FIG. 125.

Such an engine affords an example of the combination of Hornblower's method of working with that of Mr. Cowper. Steam from the boiler enters A and exhausts into B, the pistons in A and B moving together. So far we have the ordinary double cylinder engine working the crank at R by means of the connecting rod P R. But in passing over from B to C it is necessary to connect two cylinders where the movements of the pistons cross, the crank at T being at right angles to that at R. Hence this is a case where an intermediate receiver applies, and accordingly such a reservoir is placed at E and acts as a boiler for the pair of cylinders C and D. These two latter cylinders are a mere repetition of the first pair, with a common piston rod, and equal length of stroke. In order to keep up the pressure of the steam the receiver E is surrounded by a jacket filled with steam direct from the boiler.

The work done is that of driving the machinery of a cotton mill having 48,000 spindles, with all the requisite preparation, and the steam is produced from two steam boilers of the double-flued Lancashire type, each 30 feet long by 7 feet in diameter, with furnace flues 2 feet 10 inches in diameter, which are crossed by five conical water tubes welded into the flue rings. The blow-off pressure of the safety valves is fixed at 110 lbs. per square inch. The shell and fire-box of the boilers are made of steel plate, and the flues are put together with Adamson's flanged seam formed on flue rings in 3-feet lengths. It is estimated that—

Total heating surface in the two boilers is	.	1,712 sq. ft.
Heating surface per square foot of firegrate	.	25·9 "
" " per indicated H.P.	. .	3·17 "

The receiver is formed like a portion of the furnace flue of a boiler, being a cylinder with flanged joints and crossed by conical pipes, which increase the superheating surface. It is surrounded by a cylindrical casing having flat ends, and with flanged joints, the object being to obtain a strong superheating vessel which shall keep up the temperature of the steam after exhausting from B. The temperature of the boiler steam is given at about 344° F.

In an account of the performance of the engine it is stated that steam at 92 lbs. pressure enters A, where it exerts a mean effective pressure of 34·9 lbs. It then exhausts into B, entering that cylinder at a pressure of 57 lbs., and exerting a mean pressure of 26·1 lbs. From B it passes into the receiver E.

Steam for the supply of the cylinder C is drawn from the receiver, and enters at a pressure of 19 lbs., its mean pressure being 14·85 lbs. It finally exhausts into D, entering at an initial pressure of 1·5 lbs., and exerting a mean effective pressure of 9 lbs. From D it passes into the condenser.

The engine has a stroke of 5 feet, and makes 43 revolutions per minute. The diameters of A, B, C, and D are 17, 22½, 30½, and 42 inches respectively, whereby the piston constants for A, B, C, and D may be obtained by multiplying 430 into the area of each respective piston in inches, and dividing by 33,000. This gives the following numbers for the piston constants, namely:

2·957, 5·18, 9·36, and 18·05 for A, B, C, and D respectively.

$$\therefore \text{Indicated H.P.} = 2{\cdot}957 \times 34{\cdot}9 + 5{\cdot}18 \times 26{\cdot}1 + 9{\cdot}36 \times 14{\cdot}85 + 18{\cdot}05 \times 9.$$

$$= 103{\cdot}2 + 135{\cdot}2 + 139{\cdot}0 + 162{\cdot}4$$

$$= 539{\cdot}8$$

The consumption is stated by Mr. Adamson to have been, on one particular trial, as low as 1·77 lbs. per H.P. per hour.

FOUR-CYLINDER COMPOUND MARINE ENGINES.

165. We conclude this chapter by referring to some four-cylinder compound marine engines, designed by Messrs Maudslay, Sons, and Field, and fitted in the vessels of the White Star line of mail-steamers which make the voyage between Liverpool and New York. Similar engines have also been fitted in other vessels. They work to about 5,000 H.P., and exhibit a remarkable economy in the consumption of fuel; presenting, in fact, an admirable practical illustration of the excellence of the system now adopted in powerful steamships.

The writer is enabled to present two external views of the engines in question, as well as a section through the cylinders and valves, which latter will give the student a complete insight into the method of distributing the steam.

Fig. 126 is a front elevation of the engines; fig. 127 is a side elevation, showing also a section of the vessel; and fig. 128 is a section through the cylinders. But inasmuch as a section perpendicular to the screw-shaft does not take in the valves and steam passages, the drawing in fig. 128 is altered hypothetically, and the valves are supposed to be brought round into the plane of section. In this way one diagram suffices for exhibiting both the working of the valves and the connection of the pistons with the screw-shaft.

To begin with the smaller, or high-pressure cylinder, which is 48 inches in diameter, with a stroke of 5 feet. Steam from the boiler, at a pressure of 70 to 75 lbs. per square inch, enters the outer slide case on its way to the cylinder. The periods of admission, cut-off, and exhaust are regulated by two valves, one of which works at the back of the other; the first, or expansion valve,

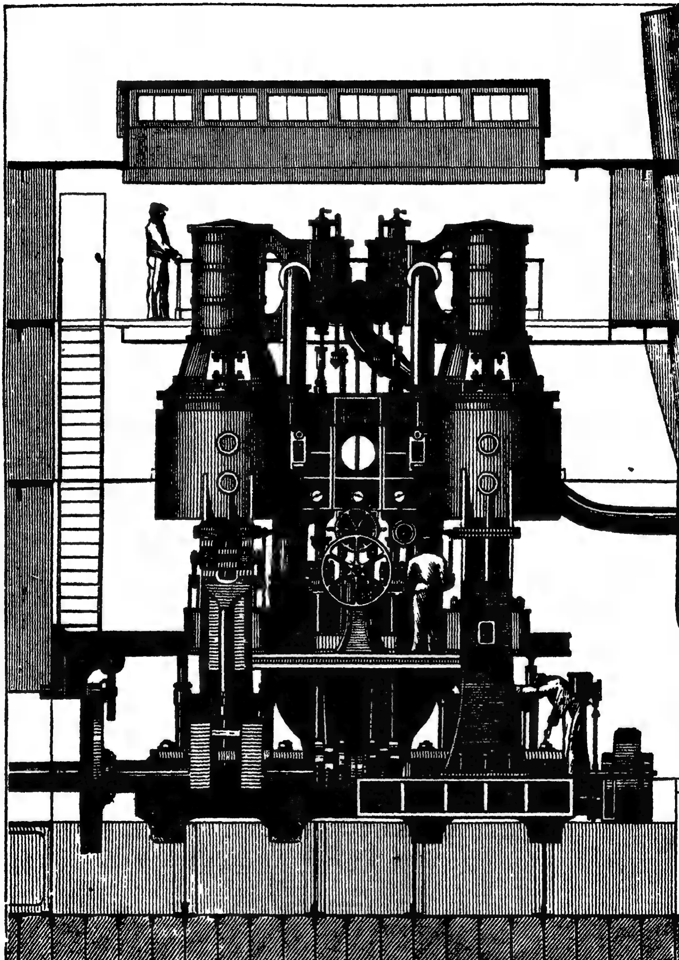


FIG. 126. Four-cylinder marine engines by Messrs. Maudslay, Sons, and Field.

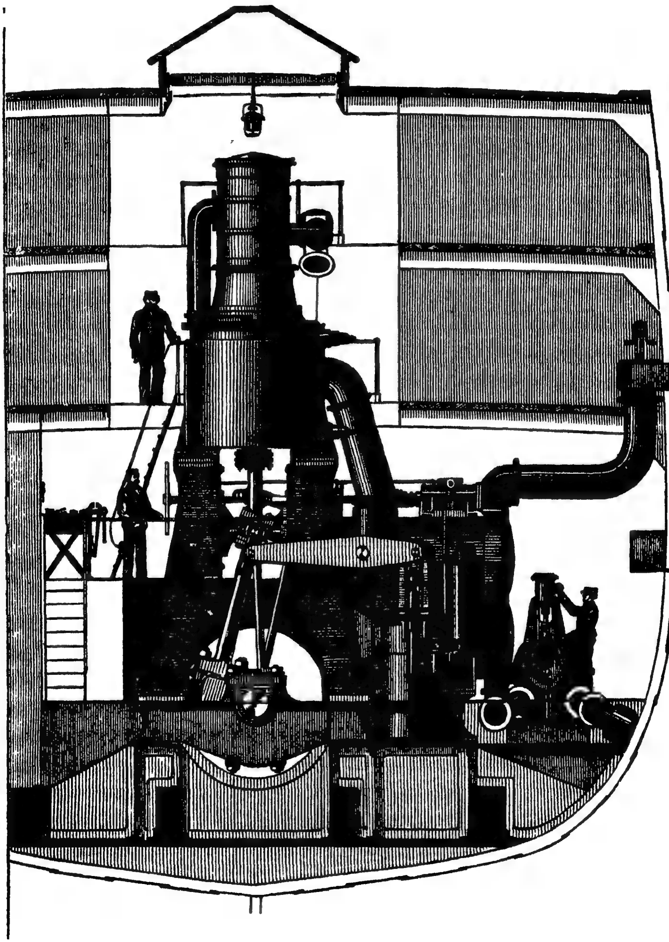


FIG. 127. Side elevation of the same engines.

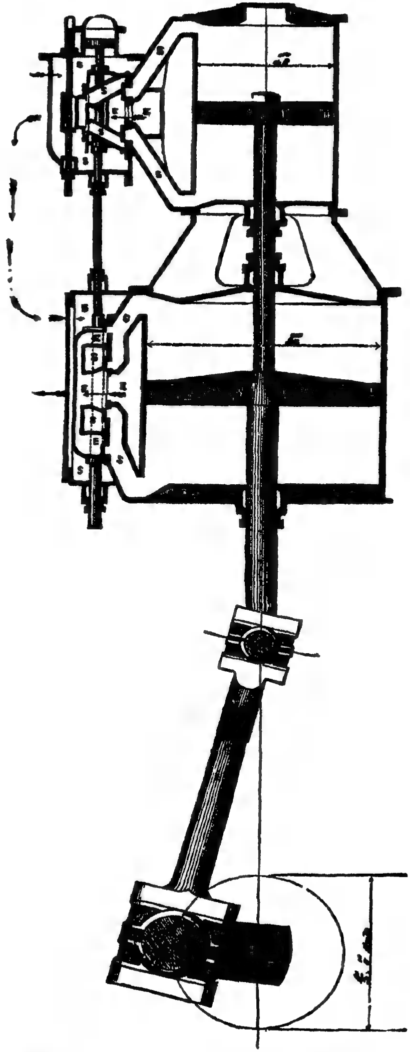


FIG. 128. Section through cylinders.

being a gridiron or plate valve, and the second being an ordinary slide, with the addition of two thoroughfare steam passages. In order to make the diagram more clear the letter S is marked on the spaces through which the steam passes on its way from the slide case to the cylinder, and the letter E is marked on the exhaust passages. A series of arrows will serve to trace out the pathway of the steam, by which we note it as entering the slide case, passing out through the exhaust, and descending to the low-pressure cylinder until it finally escapes into the condenser. The whole matter is at once apparent from the drawing.

Passing on to the low-pressure cylinder, which is 83 inches in diameter, and has also a stroke of 5 feet, we find that the section here is the same as that of an ordinary double-acting condensing engine, and the only point to be noticed is the application of the double-ported construction of valve, whereby the effective opening for steam is doubled for a given amount of travel over the ports.

The main slides of each pair of high and low pressure cylinders are on one rod, and are worked by one pair of eccentrics with a link motion. The cut-off slide at the back of the high-pressure slide is worked by an independent eccentric.

On the platform in the front elevation are three wheels, whereof the lower one is for reversing the engines, and the upper, or star wheel, is for altering the grades of expansion, while a small wheel to be seen just over the head of the engineer is in connection with the steam regulator valve, which is here of the double-beat type.

The air-pump is single-acting, and we refer to fig. 117 for an example of a single-acting air-pump with indiarubber valves. As to valves of this construction, we may state that in the early days of the marine engine the valves connected with the air-pump were of brass; but, when screw propeller engines were introduced into the navy, and the number of revolutions made per minute by the shafting was greatly increased, it became necessary to provide valves which should be better adapted for rapid opening and closing. Accordingly, canvas valves were tried, but for only a short time, as it soon became apparent that indiarubber disc valves were much more convenient for use.

The drawing shows the feed valve-box of a marine engine fitted with indiarubber valves.

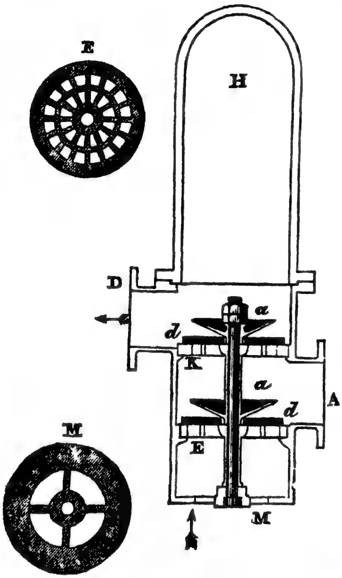


FIG. 129.

It should be understood that there is a plunger pump on the side of the pipe marked A, and that the action of the pump is to suck water up through the opening at M. The lower valve E is therefore an ordinary suction valve, while the upper valve K is a delivery valve. Looking at the valve E, there is : 1, a grating, shown in plan separately at the top of the drawing, and marked E; 2, an indiarubber circular disc, shown tinted in the sketch ; 3, a guard *a*, being a conical shield, which prevents the disc from rising too high when forced up by the ascent of the water. In the Allen engines, which make 200 strokes per minute, the indiarubber valves are rendered more quick in their action by means of springs fitted at the back. There is also the delivery valve marked K, which is the exact counterpart of E. The opening for the suction is shown separately in plan, and is marked M. Also H is an air-vessel for sending forward a continuous stream of water, being a contrivance generally adopted in a force-pump.

In the present engine the air-pumps are worked from a beam connected to the piston cross-head (see fig. 127), the feed and bilge pumps being worked from the air-pump cross-head, which is provided with guide blocks.

The drawings also show, in front and side elevation, a large cylindrical vessel which is the surface-condenser, and of which a detailed account must be given, as it is an apparatus which is essential to economy in fuel with marine engines.

According to the old system the boilers of marine engines were supplied with salt water, that is, water containing solid matter in solution, the result being, that as the water evaporated a deposit took place and formed a hard non-conducting coating upon the metal of the boiler. Two evils happened, viz., (1) the passage of heat into the water was retarded, and (2) the flame concentrated its effect more than it would otherwise have done on the material of the boiler.

The remedy consisted in 'blowing out,' as it was termed, or in allowing the steam to force out a quantity of water from the boiler at intervals, supplying its place by fresh water from the hot-well at a much lower temperature; or otherwise a system of pumps was employed for removing the so-called brine continuously. In either case there was a direct loss of heat.

The older standard works on the steam engine are full of practical directions as to blowing out. Thus, in Mr. Main's treatise it is stated that 'blowing out should be strictly attended to while under steam at sea, in order to keep the boiler free from salt and incrustation; the common practice being to displace five or six inches of water every hour,' and so on. Directions are then given as to the method of ascertaining the degree of saturation, from which it appears that ordinary sea-water contains about $\frac{1}{33}$ of its weight of salt and earthy matter, and may by evaporation become charged with as much as $\frac{12}{33}$ parts of salt, after which it is said to be saturated and can hold no more salt in solution.

There are two instruments for ascertaining the degree of saltness of the water in a boiler, viz., (1) a thermometer, which gives the temperature at which such water will boil in the open air, and (2) an hydrometer, which indicates the higher specific gravity of water when holding a larger amount of salt in solution. Thus, water boils at 213·2° F., when containing $\frac{1}{33}$ of saline matter, but its boiling temperature is raised to 226° F. with $\frac{12}{33}$ parts of salt in solution. As to the reading of the hydrometer, a special instrument is provided, with graduations of $\frac{1}{33}$, $\frac{2}{33}$, &c., on its stem, the observation being made when the water under trial has been cooled down to 200° F.

It is stated that the proportion of solid matter should never reach $\frac{4}{33}$ of the water, as incrustation commences somewhere

about that point. This state of things corresponds to a reading of 216° F. on the thermometer.

As to the loss of heat caused by blowing out it is easy to express the same in a formula, and Mr. Main gives the necessary calculation, whereby, for example, the heat thrown away for a saturation of $\frac{3}{33}$ is to the whole heat given to the water as 6 to 100.

Where brine-pumps are employed they should be so adjusted that the quantity of water which they draw off, together with the quantity evaporated, shall be equal to that supplied by the feed-pumps. As to this, it appears that, in order to keep the saturation at $\frac{4}{33}$, the evaporation, the quantity blown out, and the feed are as the numbers 1, $\frac{1}{3}$, $\frac{4}{3}$ respectively.

SURFACE CONDENSERS.

166. For large ocean steamers the system above referred to has been given up, and in its place the method of surface condensation has been adopted. The merit of introducing surface condensers is due to Mr. S. Hall, a well-known engineer, whose earliest patent on the subject was taken out in 1831 (No. 6,204). Tredgold gives a detailed account of Hall's condenser as applied in the steamer 'Wilberforce,' and states that this vessel was fitted in 1838 with engines of 285 H.P., and that surface condensation was carried out by means of a series of copper tubes, as many as 2,374 being placed vertically in each condensing cistern. Each tube was $\frac{1}{2}$ inch in diameter and 8 feet long.

The waste steam was condensed in the tubes, and returned as water to the boiler, to be re-evaporated, and to do its work over again. At the present time it is a common practice to pass water through the tubes and to allow the waste steam to fill the intermediate space, whereby the surface condenser only differs from an ordinary jet condenser in respect that the cold water does not come in actual contact with the steam, but is sent through the condensing vessel in a number of small streams, each of which is separated from the steam by a metal sheathing.

The air-pump is, therefore, the same in character as that used with a jet condenser, only it has less work to do. But nothing is gained thereby, inasmuch as it is necessary to provide circulating pumps for passing a supply of cold water through the tubes.

Notwithstanding Hall's effort to establish the new system we do not find that surface condensation was favoured by engineers. Thus, in 1841, the condenser tubes of the 'Wilberforce' became so much coated with mud from the Thames and Humber that they were taken out, and jet condensers were substituted. In 1859, however, the system was revived by the Peninsular and Oriental Company for the steamship 'Mooltan,' and was successful. At that time also the theory of heat was better understood, and soon the use of surface condensers for steamers of the highest class became more and more general.

In the case of the 'Mooltan' one condenser contained 1,178 seamless drawn copper tubes, each $\frac{5}{8}$ inch outside diameter, ·05 inch thick, and 70 inches in length; the total condensing surface amounting to 4,200 sq. feet. The indicated H.P. of the 'Mooltan' was 1,731, which is about one-third the power of the compound engines lately referred to.

The tubes were packed with a piece of linen tape pressed down by a screwed gland, which formed a very good joint. The condensing water flowed upwards in a stream around the tubes, which were vertical, and the current was produced by a centrifugal pump, with a disc of 36 inches in diameter, making about 200 revolutions per minute.

Mr. Bramwell, in his paper on 'Marine Engines,' describes a condenser for a marine engine of the horizontal construction in which the tubes are of brass, $\frac{3}{4}$ inch in diameter, with $\frac{3}{8}$ inch spaces. They are divided into three tiers by horizontal partitions in the water compartments at the ends; whereby the current of water from the circulating pump is first of all forced through the lower tier, then returns through the middle tier, and escapes through the top tier of tubes. The exhaust steam from the engine enters the condenser at the top and quits it at the bottom, as shown in fig. 130, whereby it comes last into contact with the coolest row of tubes. A table is appended to the paper giving particulars of the surface condenser in a number of compound marine engines, and among the list is one where the high-pressure cylinder is 46 inches in diameter, and the low-pressure 80 inches, length of stroke 39 inches, number of tubes 1,292, length of tubes 10 feet 10 inches, external diameter $\frac{3}{4}$ inch, space between the tubes ·35 inch, total condensing

surface 2,758 sq. ft., vacuum 28 inches. The circulating pump is single-acting, the barrel being 20 inches in diameter, with a stroke of 16 inches. These numbers refer to some engines by John Elder & Co., which were started in 1868.

The condenser of Messrs. Maudslays' engine is shown in the sketch. The tubes are of brass, and fill the large cylindrical

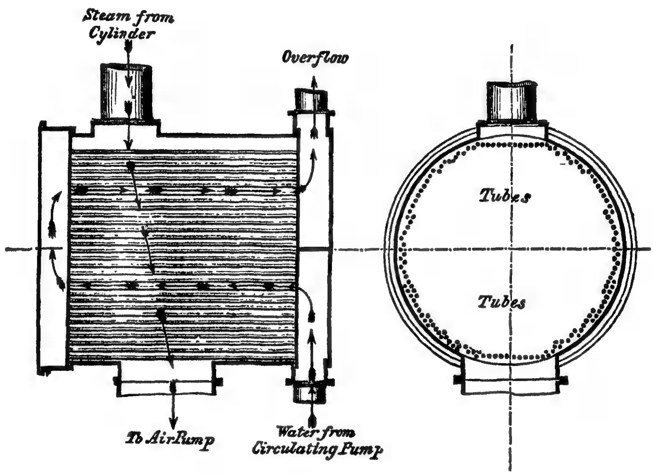


FIG. 130.

casing shown in longitudinal and transverse sections. They are indicated in the right-hand figure, and fill the whole empty space. The water from the circulating pump enters below, and encounters a horizontal plate, which causes it to pass through half the number of tubes, as shown by the arrows, and then the water returns to the right hand through the upper series of tubes and escapes by the overflow. In the meantime the steam is entering the space which surrounds the tubes and becomes condensed, only to be carried away by the air-pump and again supplied to the boiler. The circulating centrifugal pump is clearly shown in fig. 127; it is at the extreme right of the drawing.

The actual working of the engine will be understood from the indicator diagrams shown in the annexed sketch. The scale gives the amount of pressure in the original diagrams, which are here reduced in the proportion of 30 to 56. The excellence of the vacuum—viz., 28·5 inches—is especially to be noticed when

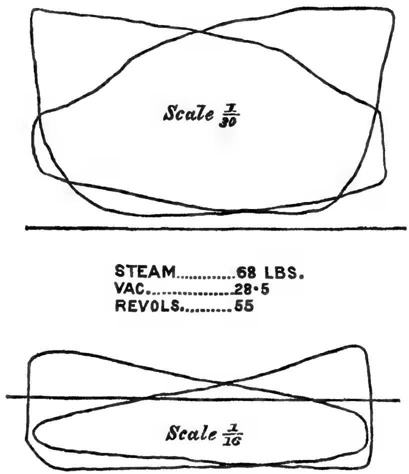


FIG. 131.

taken in conjunction with the speed of the piston; for we are told that the number of revolutions is 55 to 60 per minute. The consumption of coal speaks for itself, the record of consumption for 24 hours in an actual voyage being 96 tons, which is equivalent to 1·8 lbs. of coal per H.P. per hour. So much has already been said on this subject that it is unnecessary to add anything further, but we may at least point out that a powerful testimony to the truth of the theory of heat is afforded by the increased economy of our resources as consequent upon a systematic endeavour to apply and put in practice the principles of that theory. It is further stated that the speed of the vessel has been maintained at 19 statute miles per hour for periods of twenty-four hours at a time.

CHAPTER VIII.

MISCELLANEOUS DETAILS.

167. It has been shown that the number of strokes made per minute by a single-acting engine is adjusted by the action of the cataract, but in a rotatory engine, such as may be suitable for driving machinery, the regulation is of necessity different, and the problem resolves itself into a question of controlling the rate at which a driving shaft performs its work. Referring to the case of a clock train, where the multiplication of velocity between the driver and the last follower is considerable, it is well known that the best regulation has been obtained by the combination of a pendulum with an escapement. Such an arrangement involves, however, a step-by-step movement, which is quite inapplicable for heavy mechanism. Nevertheless, Watt appears to have been impressed with the value of the pendulum as a regulator of motion, and he determined to apply this apparatus to a steam-engine, although under a new aspect, and in a shape in which it had not previously been employed. For the complete regulation of an engine upon Watt's system two things are necessary: first, a fly-wheel or heavy rotating body possessing inertia; and, secondly, a conical pendulum. The fly-wheel constitutes the most important and primary step towards the obtaining of uniform rotatory motion. It is a heavy wheel of cast-iron, with a massive rim, which becomes, as it were, a storehouse into which energy may be poured unequally during the passage of the piston from end to end of the cylinder, but from which it may be drawn out uniformly during the operation of driving the machinery. The object of the fly-wheel is to equalise the action of the force transmitted from the piston to the crank pin, and to confine any inequality within

narrow limits of variation. But the fly-wheel alone is not sufficient for the purpose, since it is not only necessary to obtain a general uniformity of motion under the varying pressure of steam in the cylinder, but some method of adjusting the supply of steam itself is also required, whereby more power may be exerted when the resistance outside the engine increases, and less when the contrary happens. (Refer to 'Principles of Mechanics,' Art. 40).

THE REGULATION OF AN ENGINE.

It is with this latter object in view that the pendulum governor was invented. That instrument consists of a pair of heavy balls suspended from arms centred at or near a vertical axis and caused to rotate by the engine. If the power of the steam be in excess the fly-wheel accelerates its motion, the balls fly outwards and move the lever of a throttle valve, so as to diminish the supply of steam; whereas, if the power of the steam be in defect the balls collapse and the throttle valve opens more widely. The apparatus is called a pendulum governor, because the time of a revolution is affected by the length of the axis of the cone formed during the rotation, in a manner analogous to that in which the time of oscillation of an ordinary pendulum is affected by the length of the pendulum rod.

168. In order to comprehend the principle of the conical pendulum it is necessary to revert to the consideration of the law under which a body will move in a circle. This law was fully established by Newton, who proved that whenever a body describes a circle with a uniform velocity it must be subject to the action of a constant force tending towards the centre of the circle. The analytical expression of the law is the following:—

Let w be the weight of the body,

v its velocity at any instant,

r the radius of the circle in which it moves.

Then force towards centre $= \dfrac{\text{w}\, v^2}{g r}$.

169. This proposition being clearly laid down, it becomes evident that we can imitate in a body at rest the conditions which obtain during circular motion by supplying a force equal and opposite to the force which sustains the circular motion.

For example, drop a marble into a flat circular dish with a deep rim running round it. Set the dish in rotation about an axis through its centre and perpendicular to its plane, and the marble will run to the side and press against the rim. The side will react upon the marble and supply the centre-seeking force necessary for circular motion, according to Newton's statement.

If, therefore, we wished to imitate, when everything is at rest, the action which is going on during the rotation, it would be merely necessary to press the marble against the side of the vessel with a force equal to that which before kept up the circular motion. The result is that during actual rotation there is a *force tending towards the centre*; but when all is at rest the effect of rotation is imitated by supplying a force equal to the former and *tending from the centre outwards.*

It follows as a consequence of this way of looking at the subject that a problem in dynamics may be treated as a simple question of equilibrium, where the forces balance each other.

To apply the method to the case of a conical pendulum it is only necessary to supply a force $\frac{W v^2}{g r}$, acting outwards, and the parallelogram of forces is at once applicable.

Let D represent a body of weight W, suspended at C by the string C D and describing a horizontal circle of radius D B with a uniform velocity v.

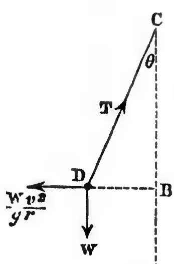


FIG. 132.

Let C B $= h$, B D $= r$, C D $= l$, also let T be the tension of the string D C, and t the time of a revolution. Applying our principle, we shall suppose the body D to be at rest and to be acted on by three forces, viz., (1) its weight, (2) the tension T, and (3) the force $\frac{W v^2}{g r}$ acting from the centre outwards.

Since D is at rest on this hypothesis, we have

$$\frac{W v^2}{g r} : W :: r : h \therefore \frac{v^2 h}{g r} = r, \text{ or } v^2 h = g r^2.$$

Also the motion is uniform; therefore $2 \pi r = t v$, and

$$\frac{2 \pi r}{v} = 2 \pi \sqrt{\frac{h}{g}}.$$

Hence the time of a revolution varies directly as the square root of C B; that is, as the square root of the height of the cone described by the string supporting W.

COR. 1. If we refer to an ordinary pendulum of length C B or h, swinging through a very small arc, the time t' of a vibration in one direction is given by the equation

$$t' = \pi \sqrt{\frac{h}{g}}, \text{ hence } t = 2\,t.$$

COR. 2. If n be the number of revolutions made per minute by the weight D, we have $t = \frac{60}{n}$,

$$\therefore n = \frac{30}{\pi} \sqrt{\frac{g}{h}}.$$

COR. 3. Let L be the length, in inches, of a pendulum oscillating once in one second in London, then

$$1 = \pi \sqrt{\frac{L}{g}} \therefore L = \frac{g}{\pi^2} = 39{\cdot}1393.$$

By substitution we have $n = 30 \sqrt{\frac{L}{h}} = \sqrt{\frac{35225}{h}}$

$$\text{or } h = \frac{35225}{n^2}.$$

EX. If $h = 18$ inches, $n = 44$, and it is easy to form a table with corresponding values of h and n.

COR. 4. It is a well-known experimental fact that if the velocity of rotation be increased the cone will flatten out, the weight W rising more nearly to a level with C. In order to deduce this result from the formula let ω be the angular velocity of the line B D round the centre, B, whence $v = \omega\, r$.

$$\therefore \omega^2 r^2 h = g\, r^2 \text{ or } \omega^2 h = g.$$

$$\text{But } h = l \cos \text{DCB} = l \cos \theta \text{ suppose}$$

$$\therefore \omega^2 l \cos \theta = g, \text{ and } \cos \theta = \frac{g}{l\,\omega^2}.$$

If ω be increased, $\cos \theta$ is diminished, and θ is increased, whereby D moves up into a higher position.

170. There is another observed result which will carry us on in

the investigation, viz., that if a cylindrical vessel partly filled with water be whirled round a vertical axis coinciding with the axis of the vessel, and at a uniform velocity, the water will be hollowed out into the form of a cup, the particular surface exhibited being that known as a paraboloid of revolution.

In other words, if A be the vertex of the cup, C A being the axis of rotation, any section of the surface, such as D A, made by a plane through the axis, is a parabola.

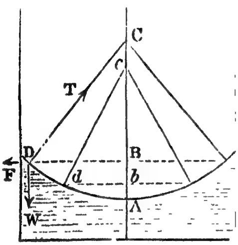


FIG. 133.

Note.—The curve called a parabola is frequently met with in studying mechanics; it is, very approximately, the path described by a ball when thrown obliquely into the air, and may be the curve formed by the section of a right cone as made by a plane parallel to a generating line, or slant side, as it is commonly called.

By reason of the mobility of the particles of water it is a property of this substance, in common with other liquids, that the pressure at all points of a surface formed upon it when at rest is the same. If it were not so the particles would move along the surface. But the water in the vessel is permanently rotating with a uniform velocity, and is, therefore, in an artificial state of equilibrium. Hence a particle at D will remain at rest just as much as a particle at *d*. Draw D C, *d c* perpendicular to the surface of the water at the points D and *d* respectively. Then D and *d* move with the same angular velocity round the axis C A. Let this angular velocity be ω, and we have

$$\omega^2 \times CB = g,\ \omega^2 \times cb = g, \text{ whence } CB = cb.$$

It is a property of a parabola that the subnormal is constant, and the term 'subnormal' is merely a technical name for the line C B, being the part of the axis intercepted between any two lines, such as D C, D B, whereof D C is perpendicular to the curve and D B is perpendicular to the axis A C. As soon as we knew that the section of the fluid cup was a parabola it became possible to predict that property of the curve which is now referred to.

171. The investigation of the property of a parabolic curve as

applied to a conical pendulum will have prepared the student for understanding the so-called parabolic governor. It appears that in 1851 a governor was brought over from Vienna where the pendulum balls rode on guides having the form of a parabola. This governor had, as we might anticipate, the fault of being too sensitive. The balls rose to the highest point or fell to the lowest on the smallest variations of speed, and it became necessary to diminish this extreme sensitiveness by attaching to the sliding collar of the governor an air cylinder or cataract, whereby in rising or falling the balls were made to suck in or force out air through a a small adjustable aperture in the top of the cylinder.

172. It may now be convenient to refer to some working models, deposited by Mr. Head in the Museum at South Kensington, which are intended to illustrate (1) the common pendulum governor, (2) Watt's governor, and (3) an approximate parabolic governor; and we should premise that in applying the conical pendulum to an engine the chief point to notice is that the number of revolutions made per minute depends upon the height of the cone, viz., C B, in fig. 134.

1. The common method of constructing the governor has been that shown in the sketch. The balls are suspended at the points E and H, a little on either side of the central vertical spindle C B. Each arm, as H D, is connected by a link to a sliding block S T. As the rate of rotation increases the balls fly out, S T rises, and in doing so actuates a lever which controls a steam valve and diminishes the supply of steam.

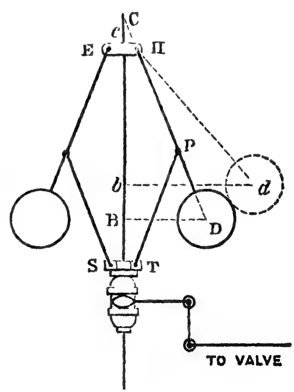


FIG. 134.

The effect of placing E and H at a little distance from the axis C B is to cause the variation in the height of the cone to become greater for any given rise of the balls, and thereby to render the governor less sensitive. Thus the heights of the cone in the two positions shown are C B and $c\,b$ respectively, the variation being equal to C c + B b.

2. In the governor as made by Watt, of which there is an example at the Patent Museum, the variation in height of the cone was much reduced. The centre of suspension was set in the vertical axis, and a jointed parallelogram C E was attached to the suspending rods, the angles D C P, F C Q being rigid and invariable. It followed that as D moved up into the position *d* the vertex E would descend to *e*, and the variation in the height of the cone would be B *b*, which is certainly less than in the previous construction. The valve lever was actuated from the point E, instead of from B, and on the whole a considerable rise and fall in the point E was secured by an extremely small change of height in the described cone. The governor was driven by a cord passing over a grooved pulley at H. It is stated that Watt's original governor would begin to rise at 36 revolutions, and would reach its maximum height at 38, corresponding to a variation of only $5\frac{1}{2}$ per cent. in the speed of the engine.

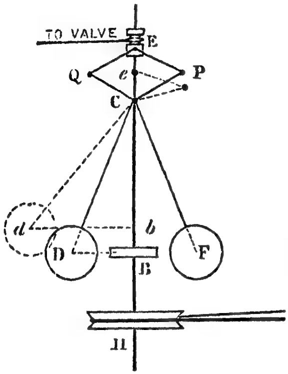


FIG. 135.

3. The approximate parabolic governor was designed by Mr. Head, and is shown in fig. 136. It will be seen that the points of suspension are on opposite sides of the central vertical line round which the balls rotate. The apparatus is, therefore, termed a 'crossed arm' governor, and the peculiarity consists in this, viz., that by properly adjusting the centres E and H to the lengths of the arms it can be provided that the arc D *d*, in which either ball moves, shall be approximately an arc of a parabola.

The following construction may be taken for setting out the governor:—The balls, being on a level *d b*, and revolving in a cone whose altitude is *c b*, are required to make a certain number of revolutions per minute, as shown by the formula. Draw *d t* perpendicular to H *d* and bisect *b t* in *a*, then *a* will be the vertex of a parabola passing through *d*. The rise from *b* to B for a higher velocity is then assigned according to any proportion which

may be thought desirable; and by a property of the curve we have

$$\text{DB} : db :: \sqrt{a\text{B}} : \sqrt{ab}.$$

This determines the point D, and other points in the curve may be assigned in like manner; after which it is only necessary to select a centre H which shall give a circular arc passing approximately through the points so determined.

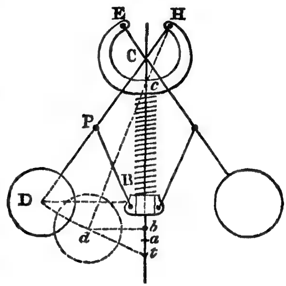


FIG. 136.

A comparison of the three modes of construction is given by the model, wherein the different governors are connected with the same driving wheel and move at the same rate. On setting them in motion the first to open out fully is the crossed arm governor, then follows that of Watt; and the least sensitive apparatus is the common governor. On reducing the speed the balls fall in the reverse order, viz., (1) the common governor, (2) Watt's governor, (3) the crossed arm governor.

In practice the last apparatus would be too sensitive, and accordingly a spiral spring is placed upon the spindle, as indicated in the sketch, the object being to retard the balls during their ascent. The spring is under no compression when the balls are in their lowest position, but offers a slight and increasing resistance as they rise; and the governor is thus rendered a practical instrument, instead of being a mere mathematical abstraction. For example, at the Newport rolling mills, Middlesborough, this governor has been applied to a large single cylinder horizontal engine driving two plate-mills. The engine makes about 40 revolutions per minute; and when nothing is passing through the rolls the balls remain in their highest position, but when the plates are passing through the rolls the arms collapse, admit full steam, and rise again as soon as the work has been done.

173. The weighted pendulum governor is a form frequently used, and is shown in fig. 117. It consists of two small pendulum balls, weighing from 2 lbs. to 3 lbs. each, and attached by links passing downwards to a collar on the driving spindle, which

carries a weight varying from 50 lbs. to 300 lbs., according to the size of the governor. The balls revolve at a high speed, making from 200 to 300 revolutions per minute. Suppose that the rods carrying the balls are equal in length to the links connected with the suspended weight W, then it is clear that for any small displacement the vertical rise of W is twice that of either ball.

Let P be the sum of the weights of the two balls, and let there be a small increase of velocity; then the centrifugal force is the same as in an ordinary governor, but the weight raised is different, for when P rises through a small vertical space W is raised, by the arrangement of linkwork, through twice that space. It follows that the height of the cone is to that of an ordinary pendulum as $P + 2W : P$, and that the sensitiveness is increased in the proportion of P to $P + 2W$.

SIEMENS' CHRONOMETRIC OR DIFFERENTIAL GOVERNOR.

174. If the governor of an engine were absolutely perfect it would regulate the velocity of the machine to one uniform, undeviating speed, and would not suffer any departure from that definite rate of motion. Such a governor would adjust the supply of steam exactly to the demands made upon it, and would in effect cause the machinery to move at one constant rate.

The governor by Watt makes no pretension to realise this ideal perfection, and does nothing more than *moderate* the inequalities to which a steam engine is liable under varying conditions of load. So far from being perfect it is subject to two principal defects, which are well known to exist, but which do not detract from its general utility as the most effective of any simple apparatus for regulating the speed of an engine which has yet been devised.

1. Watt's governor cannot prevent a permanent change in the speed of the engine when a permanent change is made in the load; that is evident; for suppose that the load were diminished, and that the speed were required to remain constant, such a result could only be obtained by reducing the supply of steam, whereas the governor fails to reduce the supply unless the balls open out more widely, or unless a correspondingly higher rate of motion is maintained.

In order to retain one uniform speed two things appear to be necessary, viz., first, that the pendulum constituting the governor should be driven by a constant force, in which case its rate of motion could be prescribed definitely beforehand, and would remain invariable; and, secondly, the engine should be compelled to adapt its own motion to that of the invariable pendulum by some mechanical contrivance which should forbid any deviation.

Mr. Siemens has endeavoured to carry out the conception stated above: he drives the pendulum by a raised weight, and pours into it a little excess of maintaining power, which excess is absorbed by friction. The pendulum, therefore, revolves at a constant speed, and the apparatus for tying down the engine to the rate of the pendulum is a differential train of wheels, which will be described immediately.

2. The second defect is that the governor does not begin to act until a sensible change has occured in the speed of the engine; for the balls do not open out more widely until after the velocity has increased, nor can they rise until an additional store of energy sufficient to overcome the friction or inertia of the moving parts has been accumulated.

Mr. Siemens' invention is directed also against this second defect, for by the operation of the differential motion it results that the whole energy stored up in the revolving balls is ready to act upon the steam-valve at the first instant that the engine attempts to deviate from the pendulum; whereas in the ordinary governor the additional energy stored up in the balls by increased velocity of rotation is the power available to control the valve. One action is slow and comparatively feeble, the other is instantaneous, and cannot be resisted.

The annexed sketch shows an elevation of Siemens' governor partly in section, together with a plan of the levers between the train of wheels and the raised weight. The differential motion is made up of the mitre wheels A, B, B, and *c*, whereof A is keyed to the vertical spindle, and is driven by the engine, while *c* rides loose upon the same spindle, and is connected directly with a heavy conical pendulum enclosed in a casing *d*, *d*. B, B are two separate wheels, carried on a hollow spindle, through which the driving spindle passes, and in gear with both A and *c*. The dif-

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ferential motion is made up of the three wheels A, B, and *c*, the fourth wheel being merely put in to equalise the driving pressure on the two sides of the vertical spindle; and it is well known that where three equal bevel wheels, as A, B, *c*, are in gear the velocities of A and *c* are equal and in opposite directions. Also as long as the velocities of A and *c* remain equal and opposite B will rotate on its axis but will not shift its position; whereas on the smallest difference between the motions of A and *c* the wheel B must begin to run round them, and it is only by so running round that a difference in the velocities of A and *c* becomes possible.

It further remains to connect the weight W and the throttle

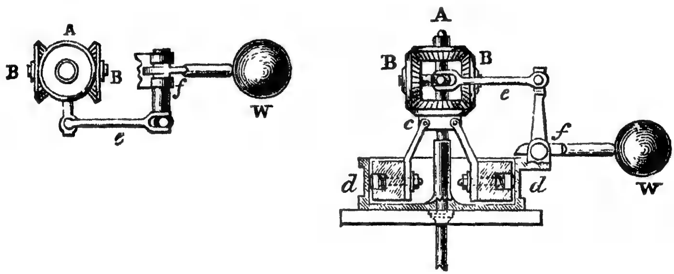

FIG. 137.

valve with the differential train of wheels. This is done by attaching W to the end of one arm of a bell crank lever whose fulcrum is at *f*, the other arm moving in a different vertical plane, and being connected by a link *e* to a short projecting rod which acts as a handle to shift the wheels B, B round A or *c*. The axis of the valve spindle passes also through *f*, whereby, on turning the bell-crank lever, a throttle valve is more or less opened and the supply of steam is regulated.

A model of this governor is deposited in the Museum of the Patent Office. The wheel A is driven by hand, and on examining the apparatus it becomes easy to comprehend the action of the weight W. First, move the handle suddenly, when A runs round, but the inertia of the pendulum prevents *c* from responding, and the consequence is that W is jerked upwards. Next, turn the handle

slowly, when all the wheels rotate on their respective axes, but W remains at rest. On gradually increasing the velocity we find that there is one particular speed at which W is just raised, and that it can be maintained in higher and higher positions by further accelerating the motion until it reaches a stop which defines the limit at which the governor ceases to act. As to the pendulum, that is, in fact, a small fly-wheel divided into segments, and carrying a sort of friction brake, which is pressed outwards against the casing by springs. So long as W is raised it tends to accelerate the motion of *c*, and, according to the phraseology of mechanics, it is the driver of *c*, and we have here an example of a conical pendulum driven by a raised weight, and therefore moving at a constant velocity. Also it follows that the engine must accommodate itself to the speed of the governor, for otherwise B would run round and the throttle valve would be acted upon. It is further evident that the whole energy accumulated in the pendulum would be thrown upon the valve if the velocity of A varied from that of *c*.

In the year 1866 Mr. Siemens brought to the notice of the Institution of Mechanical Engineers a new form of this governor, in which the conical pendulum was replaced by a cup of parabolic shape, open at both ends and dipping into water. In the modified apparatus the cup rotates about a vertical axis, and as it revolves the water rises in a parabolic surface and may flow over the rim. At a sufficient velocity a continual stream of water is raised, which is projected over the edge, caught upon fixed vanes, and deflected back against other vanes attached to the outside of the cup and rotating with it. Work is, therefore, continually done and a resistance is opposed whereby the velocity of rotation of the cup remains practically constant. As before, the cup is driven by a raised weight, and the only difference consists in the substitution of the liquid and the rotating cup for the ordinary conical pendulum.

DONKEY ENGINE.

175. The greater number of the diagrams on the steam engine which have been published by Messrs Chapman & Hall have been reproduced in this book, and we purpose now to describe the

arrangement of a small pumping engine, which has been photographed on wood from the large diagram.

The method here adopted of placing the pump in a line with the steam cylinder is in common use, and if the engine were of larger dimensions and placed horizontally it would represent the type of engine employed for forcing water into a full-sized accumulator. The upper part of the drawing requires no special explanation ; the throttle valve, the slide valve, the ports, and the exhaust passage are sufficiently indicated, but there is a peculiarity in the mode of actuating the slide and of obtaining the rotation of the fly-wheel which should be made clear.

Supposing the fly-wheel to rotate upon the axis F L it is apparent that the end *a* of the crank D *a* will describe a small circle round the central point of the extremity L, and that the slide S will be driven by the motion of *a* in a circle, just as if an ordinary eccentric had been constructed.

The rotation of the crank L H is obtained by a movement which can hardly be recommended as being good of its kind, and which is the converse of the motion shown in fig. 37. Instead of the pin causing the slit bar to reciprocate, we have the reciprocation of the bar R S causing the rotation of the crank L H. The example is interesting as showing one of the devices used by mechanics in the conversion of motion, as well as the utility of a fly-wheel for carrying the crank over the dead points.

As to the pump, it is unnecessary to say more than that the action is that of a common force-pump, with a suction valve at *n* and a delivery valve at *m*.

GIFFARD'S INJECTOR.

176. The invention of the injector for supplying feed-water to the boiler of an engine is principally remarkable as presenting an illustration of the direct conversion of heat into work. Before describing the apparatus it will be necessary to explain the meaning of the term 'induced current.'

Looking back historically it appears that in 1719 Hawksbee, the inventor of a double cylinder air-pump, showed that when a current of air was sent through a small box—entering by an opening

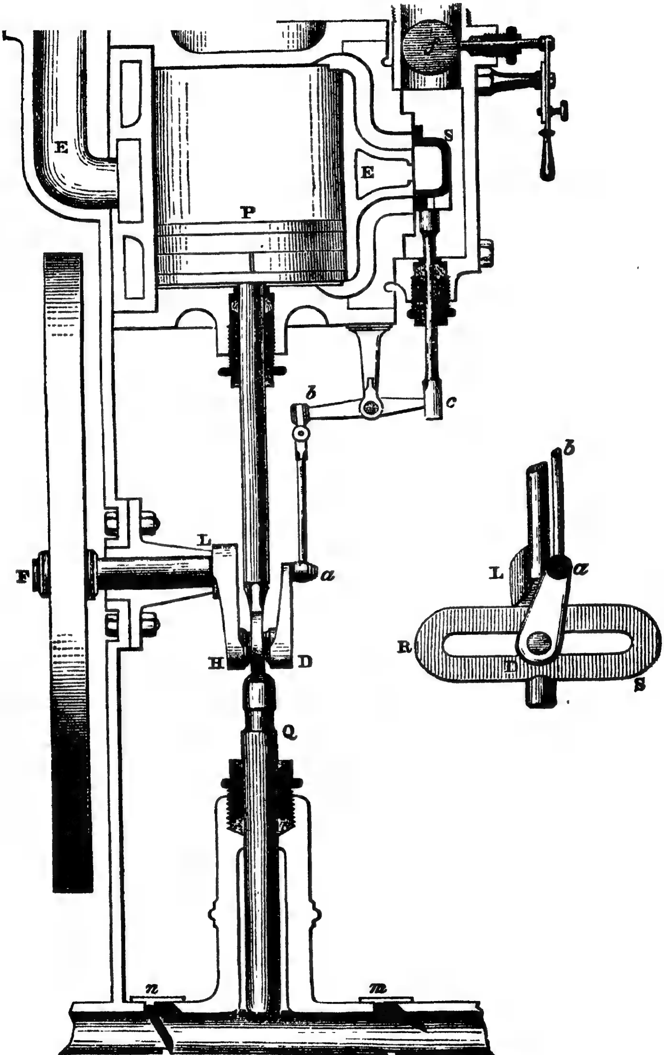

FIG. 138.

at one side near the top and escaping by a corresponding opening at the opposite side—the effect was to rarefy the air within the box rather than to compress it. It is an old experiment to suck up and drive a jet of spray out of a bottle by blowing through a horizontal tube with a contracted nozzle whose end is placed just over a vertical tube dipping into water contained in the bottle. The current of air passing over the open mouth of the vertical tube carries away some of the air from inside the tube, whereby the water rises to the top and is dispersed in a jet of spray.

According to theoretical definitions the particles of gases repel one another and have no coherent action among themselves. In practice this is not the case; and if a definite current of air be set up in a mass of air at rest, as when a jet escapes from the mouth of a tube, the air in motion will drag a number of the quiescent particles with it and will extend considerably the dimensions of the original current. It will, in technical language, *induce* a current also in the surrounding air.

The application of an induced current, with which we are now concerned, is exhibited in the annexed sketch. The globular vessel represents a boiler in which high-pressure steam is generated, and from which it escapes at an orifice E. The steam is discharged just inside a conical casing or nozzle, the object of which is to provide a means for setting up an induced current of air which will speedily exhaust the tube. The water, forced up by atmospheric pressure to supply the loss of air, will, therefore, issue from E, and we shall have made the first step towards the construction of an injector, viz., the discharge through E of a mixed jet of steam and water (see fig. 139).

In fig. 140, which shows a Giffard's injector as constructed by Messrs Sharp, Stewart & Co., there is a pipe marked 'steam,' which terminates in a vertical conical nozzle, having within it a solid rod or needle capable of contracting in any degree the amount of the issuing jet. On the opposite side of the apparatus is a pipe marked 'water,' which corresponds to A B in the elementary diagram, and by turning the wheel marked 'water regulator' the tinted sliding tube is brought up or down, so as to regulate the supply of water which is sucked up by the inducing action of the steam. There is here, therefore, precisely the ap-

paratus already described, together with mechanical means for regulating (1) the supply of steam and (2) the supply of water.

Near the bottom of the injector is a valve opening downwards and leading to the flanged end, marked 'delivery,' which is in direct communication with the boiler. The valve in question is

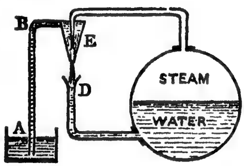

FIG. 139.

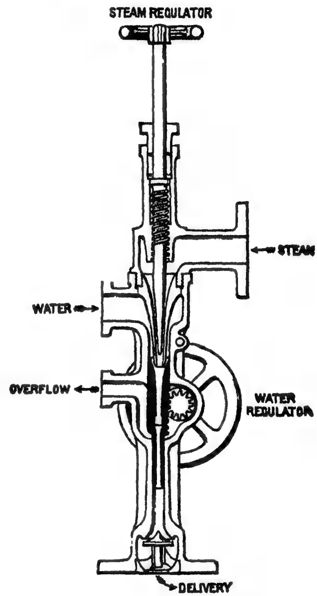

FIG. 140.

shown open in the drawing, but it is closed by the pressure within the boiler when the injector is not at work.

Recurring to the elementary diagram, which is intended to show the action in its most simple form, we may point out that M. Giffard discovered that a mixed jet of steam and water issuing from E under the circumstances above stated is competent to overpower and drive back a simple jet of water issuing from the opening D, and that a supply of feed-water may be forced back into a boiler by the steam generated therein without the intervention of any pumping apparatus whatever.

Since action and reaction are equal and opposite it is abundantly clear that a simple jet of high-pressure steam issuing from E could never drive back a jet of water issuing from D under the same pressure. It was a great step in science to conceive the idea that the absorption of heat which took place at E could furnish a source of energy directly available for doing work. There has been no parallel to this discovery in any analogous direction, and it is difficult to account for the action.

On the steam side there is the kinetic motion of the molecules of steam, and on the water side there is the motion of translation of a quantity of water, and the problem is to show a possible method of passing from the one to the other. Now, the steam issuing at E has a velocity many times greater than that of the water forced out at D. The instant that steam is liberated and escapes, the kinetic motion of its particles appears under a new form, viz., as a motion of translation, and the velocity of an issuing jet of steam is many times greater than that of a jet of water forced out by the same pressure. If, therefore, the jet of steam could be condensed by an indefinite source of cold after it had fairly got clear of the orifice it would be converted into a fine liquid line, and the velocity with which its molecules were rushing out would not be changed. The motion of heat would be diminished, but the onward motion would remain unimpaired. This liquid line would be moving at such a high velocity that it would pierce any jet of water coming towards it from the boiler, very much as if it were a steel wire forcing its way through the mass. We know of no source of cold competent to produce this result, but what really happens is the same in character though less in degree. The steam, liquefied at E, retains to some extent the higher velocity which it possessed as steam, and on the whole the aggregate energy of the water globules flowing onward at E is greater than that of the water jet coming towards them from D. The latter jet is overpowered and driven back, and a quantity of water from the cistern at A is continually forced into the boiler.

As to the velocities with which we have to deal, it appears that if the steam had an actual pressure of six atmospheres the water would issue at a velocity of about 101 feet per second, and the steam at a velocity of about 1,800 feet per second.

In dwelling on this subject there is an experiment, easy of performance, which exhibits the effect of fluid pressure in forcing out a jet of liquid, and which recalls the certainty that without the direct agency of heat, the injector would be powerless. The apparatus consists of a brass tube, say 4 feet long having a glass beaker at the top. There is a stopcock at the base of the tube, and directly opposite to it is a small open nozzle of the same bore as the stopcock which leads into the base of a glass tube about an inch in diameter. The water in A is maintained at a constant height, and it is found that the water rises in the glass tube until it reaches a level B, which approaches closely to the level of the water in A. The difference depends on the loss of energy by friction and also upon imperfections of the apparatus and the difficulty of adjusting the openings for the water so as to cause the stream which comes from A to correspond with that coming from B.

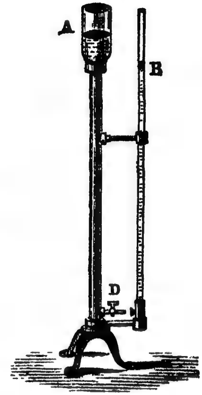

FIG. 141.

Referring again to fig. 140, it will be seen that a pipe marked 'overflow' leads out from the centre of the instrument; this pipe communicates with a small chamber in the central channel just below the level of the pinion, and is intended to allow the escape of any surplus water. When the supply of steam is properly adjusted to the amount of water sucked into the instrument no overflow takes place, whereas an excess of water or steam will at once give rise to a discharge at the overflow. In the one case the energy imparted to the water is insufficient and part recoils, while in the other case too great a condensation of steam will occur and energy will be dissipated. It is, however, easy to adjust the steam and water regulators so as to avoid any waste.

The rise in temperature of the feed-water shows the amount of energy available for doing work, and it is found that the quantity of water delivered into the boiler increases as the feed-water itself is supplied in a colder state. Thus, in one case, the temperature of the feed-water before entering the injector was 60°, 90°, 120°, and the number of gallons of water delivered per hour was

972, 786, 486 respectively. It is a confirmation of the explanation that steam at a given pressure will force water into a boiler against a still higher pressure. Thus, steam at 27 lbs. pressure forced water into a boiler where the steam was at 52 lbs. pressure, the temperature of the feed-water being raised from 92° to 170° during the operation.

LINK MOTION FOR REVERSING AN ENGINE.

177. When the piston is near the middle of its stroke in a direct-acting engine the slide-valve will have moved over the steam ports in the manner pointed out in fig. 142.

The large and small circles represent respectively the paths traced out by the centre of the crank pin and the centre of the eccentric which works the valve; and inasmuch as the slide would not be seen in a sectional drawing it is repeated in a supplemental diagram, where its position in relation to the steam ports is indicated. The method of reversal is the following :—

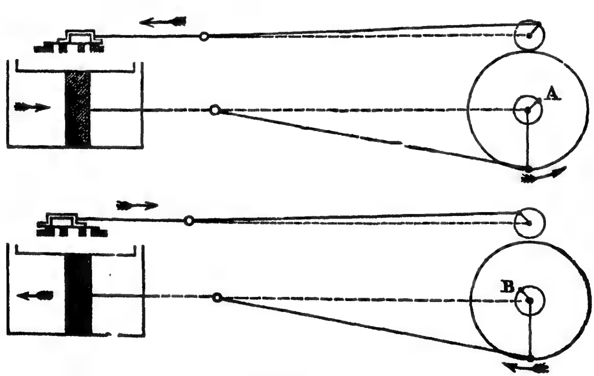

FIG. 142.

In the upper diagram the piston is moving to the right and the valve to the left, the piston having advanced so far in its stroke that the valve is returning to cut off the steam. In order, therefore, to change the motion it is necessary to drive the piston back

by admitting steam on the opposite side and by letting out that portion of the steam which is urging it forward. Hence the valve must be moved into the position shown in the lower diagram, which is equivalent to shifting the centre of the eccentric from the position marked A to that marked B. The piston will then return before it has reached the end of the cylinder, or in other words the motion of the engine will have been reversed.

It will be seen that the imaginary crank which works the slide is inclined at an angle somewhat greater than 90° to the crank which is connected with the piston, as must be the case where lap and lead are given to the valve. Further, it is apparent that the crank of the slide rod is in advance of, or leads, the larger crank in its journey round.

The explanation shows that in reversing an engine we must either shift the centre of the eccentric from the position A to the position B, or else we must employ two eccentrics and provide some means of connecting each in turn with the slide-valve.

The method of reversal by shifting the eccentric from the position A into the position B was at one time largely employed in marine engines, but it has gradually given place to the reversal by a *link motion.* That apparatus for reversing an engine has grown with the locomotive engine, and is so convenient and rapid in its action that no other can compare with it.

The link motion appears under three forms: there is (1) the shifting link, having its concave side towards the axle or crank shaft; (2) the stationary link, where the curvature is in the opposite direction; (3) the straight link, which is derived from a combination of the two former contrivances.

1. In the shifting link motion two eccentrics are keyed upon the shaft in the positions which we have agreed to call A and B; the link is an open slotted circular piece, struck with a radius equal to the effective length of each eccentric rod, and having, as before stated, its concavity turned towards the axle or shaft of the engine. The slide rod is connected with a block which moves in the slotted link, whereby the end of the rod is actuated by either of the eccentrics at will. This construction was adopted at an early period, and is known as 'Stephenson's link motion.'

2. The stationary link, which is that shown in the drawing, was

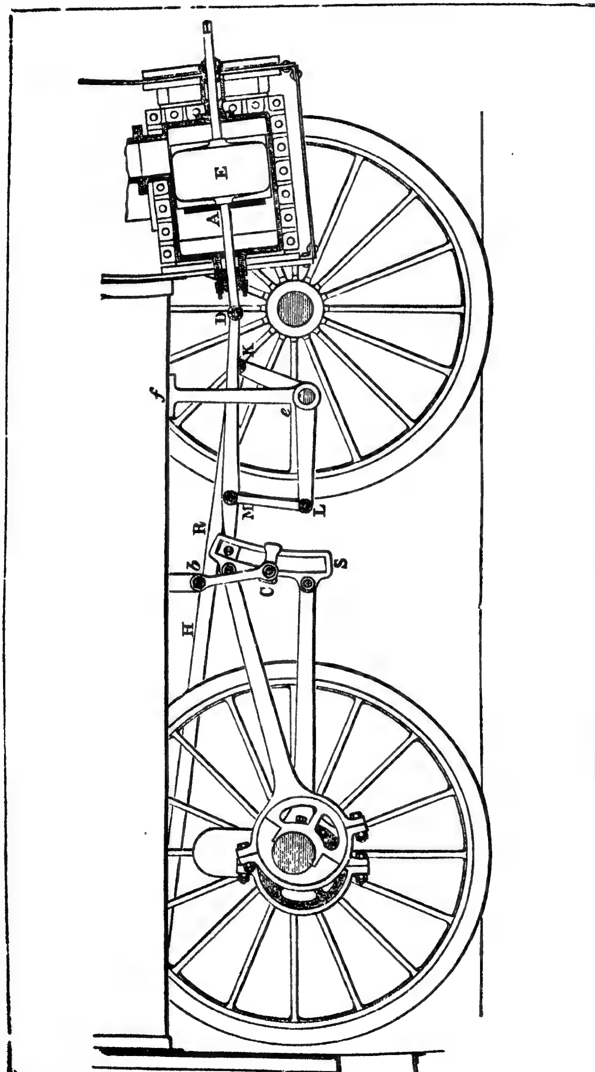

FIG. 143. Locomotive Link Motion.

invented by Mr. Gooch, of the Great Western Railway. It will be seen that the link R S is here suspended by an arm *b* C, so as to be stationary so far as any up-and-down movement is concerned, and that it is circular in form, being struck by a radius equal to D R, whereby also its concavity lies towards the cylinder and away from the axle or shaft of the engine. In the sketch the forward eccentric is in operation, and the motion is readily traced from the axle to the slide, which is shown as having partly uncovered the steam port marked A. On pulling the rod H which is in connection with the starting lever, or its equivalent, the bell crank K *e* L is moved, and the jointed rod D R is brought down by the pull of L M into a lower position, whereby it imparts to the slide the motion due to the back eccentric, and the engine is consequently reversed.

3. A third method is Allan's straight link motion, in which the link and the valve rod are both shifted in opposite directions at the same time. When the link is shifted it must of necessity be curved towards the eccentric rods, and when the slide rod is jointed as at D and shifted up or down the curvature of the link must be towards the slide, from which it follows that if both the link and the slide rod shift in a vertical plane the concavity and convexity may neutralise each other and a straight link may serve to give the motion. Link motions prove to be rather complicated pieces of mechanism when any attempt is made to analyse them thoroughly, and therefore it may suffice to say that with a stationary link the lead of the slide is maintained constant under all changes in the position of the sliding block, whereas with the shifting link the lead increases a little towards the central position.

One advantage of the contrivance consists in the power which it gives to the engineer of regulating the supply of steam admitted into the cylinder. By moving the starting lever or its equivalent into intermediate positions the amount of travel of the valve is reduced at pleasure, for it is evident that no steam can enter the cylinder when the lever is half-way between its extreme positions, and that varying amounts of opening of the steam ports, increasing to the maximum value, will occur when the lever is pushed over by successive steps.

We pass on to describe other arrangements of reversing gear

which are now of considerable practical value, and shall confine the inquiry to certain principal forms, commencing with that patented by *J. W. Hackworth*, A.D. 1859, No. 2,448.

OTHER REVERSING VALVE GEAR.

178. It will be remembered that in working a slide valve by a simple eccentric, the motion is equivalent to that of a crank C P and connecting-rod P Q, the end P being carried round in a circle while the slide S reciprocates in a straight line.

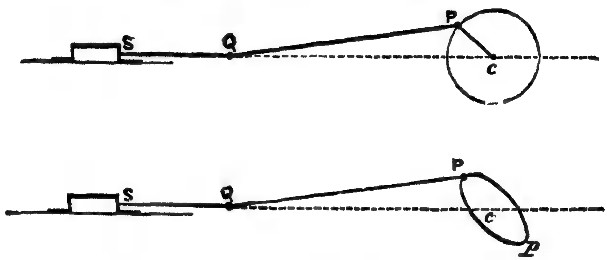

FIG. 144.

It is clear that a sufficient motion of the valve might be obtained if the point P were constrained to move in an inclined oval curve as shown in the diagram, the longer axis of the oval, viz. P *p*, making an angle with the line C Q.

This idea has been at the foundation of the class of inventions now to be considered, for it will be seen that there are many ways of getting such an oval, each of which has its advocates and is well worthy of consideration.

179. It is an elementary fact in geometry that, in the ordinary combination of a crank and connecting rod, as used in a direct-acting engine, any point in the connecting rod P Q will, as the crank revolves, describe an oval curve in the plane C P Q. This curve resembles a section of an egg, being rather more pointed at one end than the other, and is approximately an ellipse.

In fig. (1) of the annexed diagram, the end Q of the connecting rod P Q is constrained to move along the line A B, pointing to C,

and a point R in the connecting rod, selected at pleasure, will describe an oval as shown by the dotted curve.

Taking the position of the connecting rod P Q when P C Q is a right angle, it appears that if A B be turned about the point Q so as to take the position L M, or N T, the point Q will, as C P revolves, move up and down the lines L M or N T, as the case may be, and the point R will describe an inclined oval curve such as that which we are seeking to obtain. It appears also that the direction of the longer axis of the ova depends on the direction of the guiding slot in which the point Q moves.

It only remains to connect one end of the valve rod with the point describing an oval, taking care that the other end moves in

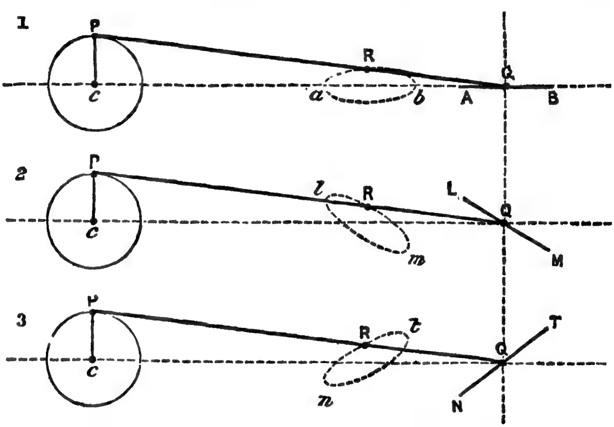

FIG. 145.

a straight line perpendicular to C Q, and we shall have a conveniently arranged valve motion which can be reversed by changing the direction of the guide as in figs. (2) and (3).

180. Having premised these introductory observations, we turn to Hackworth's specification, which states that on the main shaft of the engine and side by side with the driving crank there is placed an eccentric pulley, the extreme throw of which is directly opposite the extreme throw of the driving crank, while the throw of the eccentric must exceed the traverse of the valve.

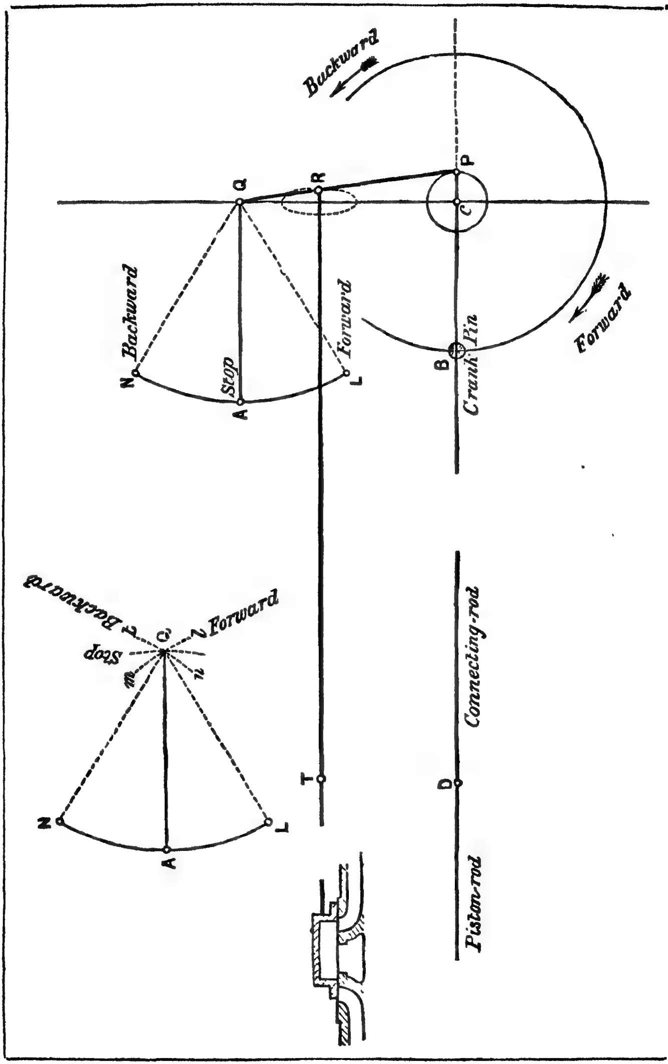
Backward
Forward
P
C
B
Crank Pin
Q
R
N
A
L
Backward
Stop
Forward
Stop
Backward
Forward
T
D
Connecting-rod
Piston-rod

FIG. 146.

The annexed lecture diagram is taken substantially from that in the specification, C P being the crank which is the equivalent of the eccentric pulley, P Q the eccentric rod, the end Q being constrained to move in the vertical line C Q, and the steam cylinder being horizontal.

C B is the crank of the engine, terminating in the crank pin B, while B D is the connecting rod. The piston is now at one end of its stroke, and it will be seen that C B and C P point in opposite directions in a horizontal line.

The valve, with its strap or spindle, is connected with a horizontal valve rod T R, jointed to the eccentric rod at the point R, which is preferably chosen so that $QR = \frac{1}{3} QP$, or nearly so.

When the crank is on the dead centre, as in the diagram, the valve is thrown back by a space on the opposite side of C Q, which is equal to the lap plus the lead.

In whatever position the bar A Q may be held it is always capable of oscillating about the end A, and it follows that if C P be rotated about C, the end Q of the eccentric rod P Q will describe a small arc of the circle whose centre is A and radius A Q, which is practically the same as if Q were constrained to move in a straight slot pointing to C.

In this state of things the port will not open any farther for steam, but when C P and C B have each made half a revolution the valve will be moved back upon the other steam port by an amount equal to the lap plus the lead, and neither port will open for steam by a greater amount than that due to the lead of the valve.

There are different contrivances for shifting the lever A Q, as to which it is easy to arrange a convenient mechanism, and we shall now suppose that A Q is shifted into the position L Q, being still free to oscillate about the end L, which is the new position of A. It follows that during each revolution of C P the point Q will oscillate in the dotted line *l m*, which is approximately a straight line corresponding to L M in fig. 145, and as this line is inclined to C Q the point R will describe an oval whose longer axis is similarly inclined to C Q.

In order to make this clear the lever A Q is shown in three positions in a separate diagram, and the corresponding oscillations of the point Q are indicated by the dotted circular arcs.

It is evident, from what has been premised, that a valve motion is obtained by setting A Q in the position L Q, and it remains for us to show that the engine will be reversed by placing the lever in the position N Q, which is equivalent to causing the point Q to oscillate in the line *n t* instead of the line *l m*.

Whether *l m* and *n t* be actually straight lines, formed by a slot in a block riding on a stud or pin, or whether they be approximate straight lines formed by small arcs of a circle, as in the main diagram, is only a question of construction. Both methods are fully set out in the specification, and we shall therefore assume that *l m* and *n t* are straight lines.

The main diagram shows the piston at the end of its stroke, and the present diagram is intended to show that the crank pin B has

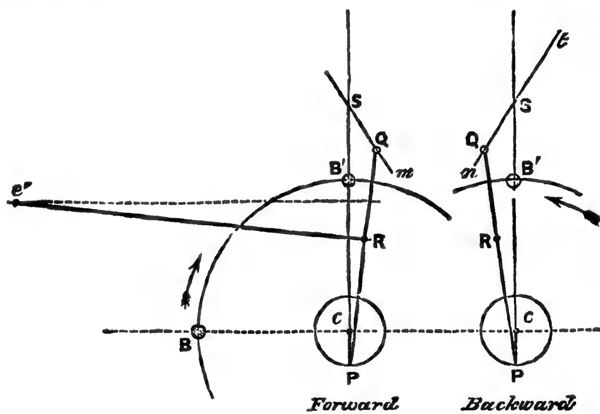

FIG. 147.

moved from B to B′ in the forward stroke, at which time the piston will be near its middle position, the valve being open for steam and the piston moving to the right.

Conceive now that the line *l m*, in which Q moves, is shifted into the position *n t* by changing the position of the reversing lever from L Q to N Q.

The effect of doing this will be at once to carry the slide to the left hand, thereby opening the steam port on the opposite side

of the piston and reversing its motion. In truth the joint of the valve rod marked T in the main diagram will be shifted from e' to e.

Inasmuch as the valve is set back by an amount equal to the lap plus the lead when H C P is horizontal, and no motion is imparted to the valve by shifting the lever A Q into the positions L Q or N Q, it is apparent that the lead remains constant for every position of A Q, whether in the direction marked *forward* or in that marked *backward*, and hence, as stated by the inventor, the *lead never varies.* This is a prominent advantage secured by the forms of valve gear now under consideration.

181. In order to appreciate from a general point of view the value of an oval curve in working a slide valve, the student should refer back to Arts. 103 and 104, where the crank of the eccentric, marked O p in figs. 78 and 79, is set back so as to make an obtuse angle H O p with the line of centres, in order to allow for the lap and lead. It follows that when the main crank arrives at a dead point the slide valve will have completed the most rapid part of its motion (which occurs when H O p is a right angle), and its velocity will have begun to diminish.

But it is just at this moment that the steam port is opening for the entrance of steam into the cylinder, when it is an advantage to quicken the motion of the valve instead of retarding it.

It will be found, on applying the oval motion, that the point R, to which the valve rod is attached, is near the apex of the oval when steam is admitted, and that in passing round this apex the valve is shifted rapidly so as to complete the full opening for steam. It is one of the advantages claimed by the inventor that the valve opens quickly when the crank is passing a dead point, or when the engine is on the centre, as engineers express it.

It is fully explained in the Elements of Mechanism that an oval curve is the result of combining in a regular manner two motions at right angles to one another, which are of proper amount and properly timed. It is further apparent that the point R is the recipient of two simultaneous movements at right angles to one another, the result of the combination being shown by the form of the oval.

Taking one of these movements as occurring in C Q, and the other at right angles to C Q, it will be easy to trace the effect of

each upon the valve and to find out when they tend to corroborate or when to neutralise each other.

In this manner the valve motion may be subjected to a complete analysis.

182. When the principle of a movement, such as that now under discussion, is well understood there will be no difficulty in suggesting modifications of construction.

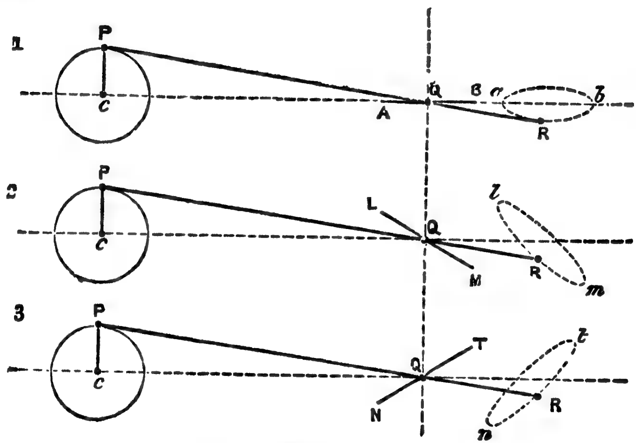

FIG. 148.

For example, it is obvious that if the point R in fig. 145 were to reside in P Q produced, as in the annexed diagram, there would be no material change in the character of the ovals traced out by the point R. In fact, the principal difference consists in the power of obtaining an enlarged curve without increasing the length of the crank.

As before, let the point Q in the connecting rod P Q be guided in the straight slots marked A B, L M, and N T, when a point R in P Q produced will, as required, trace out the ovals *a b*, *l m*, or *n t*.

In a patent of 1876, No. 4,246, Messrs. *J. W.* and *A. Hackworth* described such a modification, and their specification states that by attaching the valve rod to the overhanging end of the eccentric rod there is obtained the advantage of giving a greater travel of the valve with either a smaller eccentric or less amount

of inclination of the changeable path, which has been called *l m* or *n t* in the description given above. Indeed, the *first* claim of invention was obtaining 'increased expansion of steam through connecting the valve to the extreme end of the connecting rod.' It was further claimed that there was an admission 'of a more equal charge of steam at both ends of the cylinder at all grades of expansion.'

It is further apparent that the virtual crank of the eccentric may coincide with the main crank instead of being opposed to it, regard being had to the necessary motion of the valve, and we refer to a diagram taken from the specification of a patent granted to

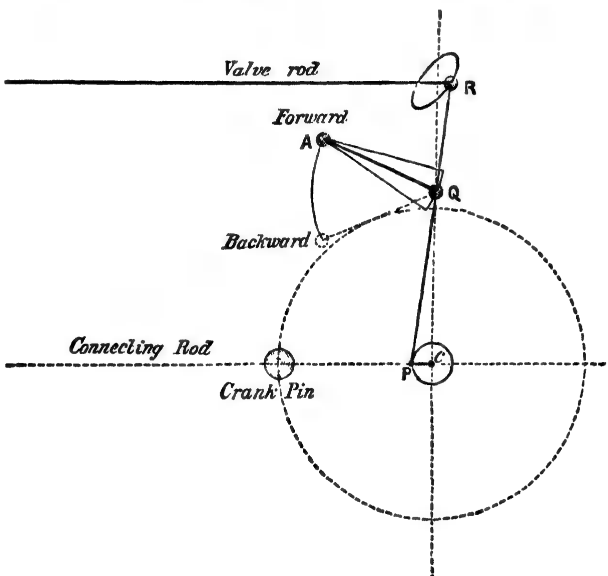

FIG. 149.

Mr. *F. C. Marshall*, the well-known engineer, in 1880, No. 4,185, where such a construction is set forth. The student may also refer to the specification of a patent granted in 1879, No. 2,138, to *F. C. Marshall*, on the same subject-matter.

The sketch is taken from the specification No. 4,185, and shows the eccentric rod P Q R having the intermediate point Q attached to the reversing lever A Q, whereby the point Q moves in the small arc of a circle centred at A.

The direction of this arc being inclined to the line C Q, and the valve rod being attached to a point R in C Q produced, it follows that the end of the valve rod will describe a small inclined oval curve such as is set out in the diagram.

The specification No. 2,138 states that the valve used with the gear therein described 'is made dissimilar ended when connected direct to the eccentric rod, having, in the case of a valve with single exhaust opening, two steam openings at the end opposite the gear and one steam opening at that other end, and in the case of a valve with double exhaust openings three or four openings for steam on that end opposite to the gear, and two only at the other end.' This is a combination of an ordinary valve at one end and a gridiron valve at the other end.

JOY'S VALVE GEAR.

183. In Joy's valve gear, which has been adopted in some engines on the London and North-Western Railway and elsewhere, and is a most valuable invention, there is no eccentric, but the oval curve is derived from a single combination of linkwork, the direction of the longer axis of the oval being varied by changing the direction of a slotted guide.

The first patent was granted in 1879, No. 929, and there have been other subsequent patents.

The nature of the invention will be apparent from the diagram, which shows its application in a locomotive engine, C being the centre of the crank shaft, and B the crank pin.

The end Q of the connecting rod B Q is constrained to move in the line C Q, while R E is a link jointed at R to the connecting rod, and attached at the end E to an arm or lever D E having a fixed centre of motion at D. Another link S T is jointed at S to R E, and carries at the point N a small sliding block which travels up and down in the curved slotted block *l m*.

The valve rod T V is jointed at T to a point in S T, and at V it

is further attached to the valve spindle. There is provision made for changing the direction of *l m* when it is required to reverse the engine.

The precise arrangement of the working parts will be explained in the next article, the present description being merely introductory.

The three principal ovals are marked out by dotted lines.

There is first an oval described by the point R, then there is an oval described by the point S, which shows a peculiarity often

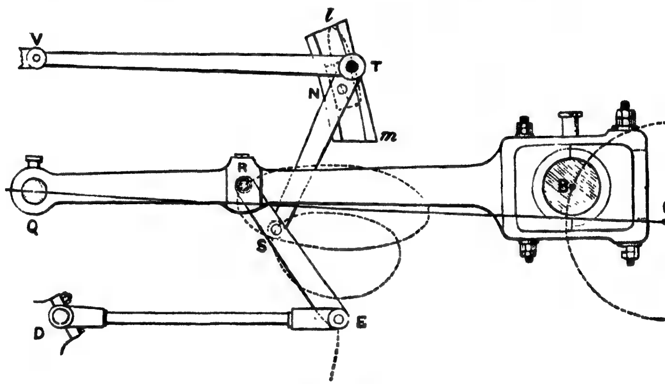

FIG. 150.

observed in the final curve on which we rely, viz. that one half is flatter than the other half.

There is finally the curve described by T, which gives the required valve motion.

184. In order to set out Joy's valve gear we proceed according to the rules stated in a short pamphlet written by the inventor, and to which the reader is referred for a more detailed account.

Let P Q C be the central line of the cylinder, C B the crank, B Q the connecting rod, P Q the piston rod, C *b*, C *b'* the positions of the crank, and *b e*, *b'e* those of the connecting rod, when the piston is at half-stroke.

Select a point on the connecting rod such that its vertical vibration between the positions *b e* and *b'e* (which is marked *c d* on

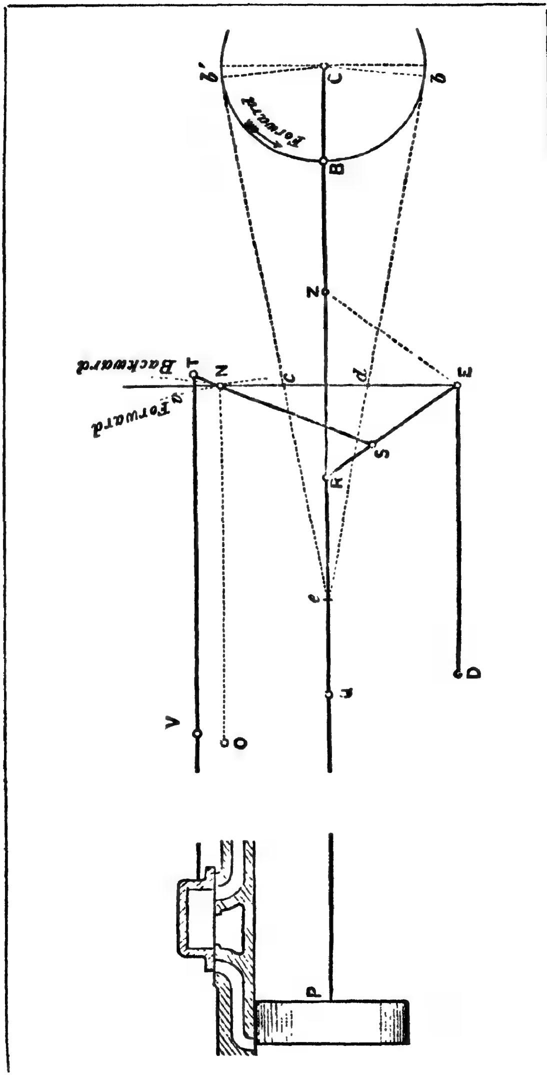

FIG. 151.

the diagram) shall be about equal to C B, being preferably a little in excess of the length of the crank.

Let R and Z be the extreme positions of the point so selected when the crank is on the dead centres. Produce the vertical *c d* in both directions, and take a point E in *c d* produced such that the angle R E Z shall not be in excess of a right angle, being preferably a little less.

The link R E connects the points R and E as shown, and the link E D has a fixed centre of motion D at some convenient point in the framework of the engine.

Taking the direction of the valve spindle line V T, which is horizontal on the diagram, mark off upon it a space *v* T on one side of the vertical line *d c* produced upwards, which is equal to the required *lap* plus *lead.*

On R E measure R S$=\frac{2}{3}$ *c d*, and join T S cutting *d c v* in N. The point N will be the centre of oscillation of a curved link, which, by assuming different inclinations to *d c v*, causes the reversal of the engine.

As the crank goes round, and the connecting rod oscillates, the point N travels up and down the curved link already referred to in the last article, and T describes the oval curve for which we have been seeking.

The curved link or slot in which the pin N travels to and fro is indicated by dotted lines in the diagram which correspond to *l m* and *n t* in the Hackworth diagram. The curve of the link is a circular arc having T V as a radius. In the diagram the radius of the curve is marked by the line N O, which is equal and parallel to T V, and Mr. Joy states that the opening of the port beyond the amount given as lead is dependent on the amount of angular motion imparted to the curved link. Also that in this gear the 'leads' and 'cuts off' for both ends of the cylinder and for backward and forward going will be practically equal, the opening of the ports being also as near as possible equal.

VALVE DIAGRAMS.

185. There is yet another matter connected with valves which should not be passed over, and that is the graphical method of representing the motion of a valve, as laid down by *Zeuner*, who

has written an elaborate treatise on the subject. We shall confine the inquiry to an elementary explanation of the so-called *valve diagram.*

When the slide valve of an engine is worked by an ordinary eccentric, the motion of the valve is that due to a crank and connecting rod; but in practice the length of the eccentric rod is so much greater than that of the crank that we may, as a first approximation, conceive that the eccentric rod remains parallel to itself during the motion. On this supposition the position of the valve during each instant of the stroke may be set out in a simple form of diagram, giving the so-called *curve of position of the valve.*

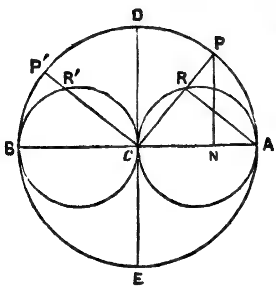

FIG. 152.

For example, let C be the centre of the circle ADBE, described by P, the centre of an eccentric pulley.

Draw the diameter ACB, and let AB represent the whole travel of the valve. Draw PN perpendicular to AB; then as P goes round in the circle the position of N will indicate the position of the valve.

On AC describe a circle cutting CP in R, and join RA. Then in the triangles CRA, CNP we have CP=CA, and angle CRA=angle CNP, each being a right angle; also the angle RCN is common to both triangles, therefore CR=CN.

Hence if CP represent the crank of the eccentric pulley, and the construction in the figure be completed, the curve ARC will give the position of N relatively to P at any instant.

It follows that as P travels round the circumference of the circle ADBE the two small circles drawn upon AC, BC as diameters are the *curves of position* of the slide valve. Thus when P comes to P′ the line CR′ represents the distance of the valve from its central position, or more accurately the distance of any point in the valve from the central position of the point in question.

If the obliquity of the eccentric rod be taken into account, the curve of position of the valve can be set out in the manner following.

Let CP be the crank of the eccentric, and PQ the eccentric

rod at any instant. With centre Q and radius QP describe the circular arc PR, and with centre C and radius CR describe the circular arc RS, cutting CP in S. Then the curve of position of the valve will be ascertained by setting out a sufficient number of points, such as S. It is given roughly by the dotted lines in the

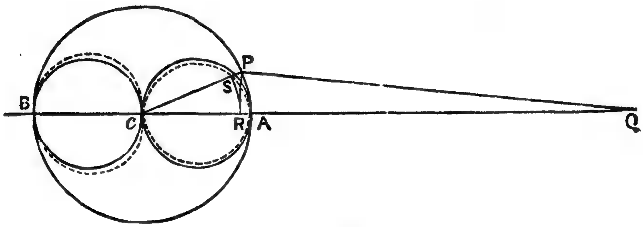

FIG. 153.

diagram, the small circles indicating, as before, the curve of position when the obliquity of the eccentric rod is neglected. The student will note that the dotted curve lies inside one small circle and outside the other. There is also a peculiarity in the shape of the curve near the point C, which cannot be shown on the scale of the diagram.

186. So much being premised, we pass on to consider the method of setting out in a single diagram the movement of the valve corresponding to any given position of the main crank of the engine.

Taking the case of a direct-acting engine, let X X′ represent the centre line of the cylinder, and let BCA be the travel of the valve, the small circles being the curves of position as found in Art. 185.

Disregard the lead of the valve, and let CE be the direction of the crank of the eccentric, when CBX is that of the main crank. Then CR is the movement of the valve from its central position, and is therefore equal to the lap of the valve.

With centre C and radius CR describe the circular arc RQS; then CRE is the direction of the crank of the eccentric at *admission*, and CS*e* is the same at *cut-off*. Also, if any line CQP be drawn from C it will represent the whole movement of the valve from its middle position, when the crank of the eccentric takes

the direction C P, and since C Q is equal to the lap of the valve it follows that Q P is the opening of the steam port for the admission of steam.

In like manner, while the crank of the eccentric moves through *d* L D we can set out the points of release and compression. Thus let C *r* be the inside lap of the valve; then the circular arc *rq* corresponds to R Q, and just as P Q shows the opening for steam so *pq* shows the opening for exhaust, the lines C L, C *l* indicating the direc-

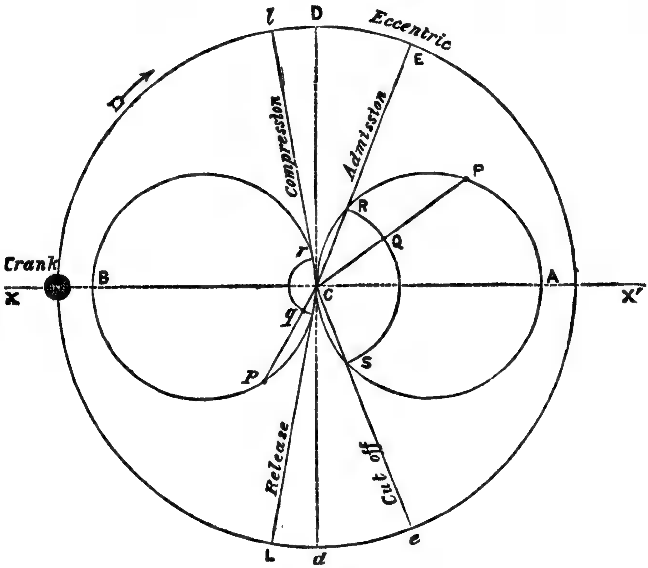

FIG. 154.

tions of the eccentric at the periods of release and compression respectively.

As yet nothing has been said about the lead, the object being to explain the principle of construction of the diagram in its simplest form, but in the next article the lead will be taken into account.

187. It remains to modify the diagram, so as to make it more convenient for the solution of problems, leaving its general cha-

racter untouched. What is really wanted is a method of recording the motion of the crank and the travel of the valve in a single diagram.

As before, let X X′ be the central line of the cylinder, and A B the travel of the valve, and let A B, D *d* be at right angles.

Let C R = lap of valve,
R T = lead of valve.

Draw T M at right angles to C A and join C M. Then, upon comparison of this diagram with that in the last article, it is clear that

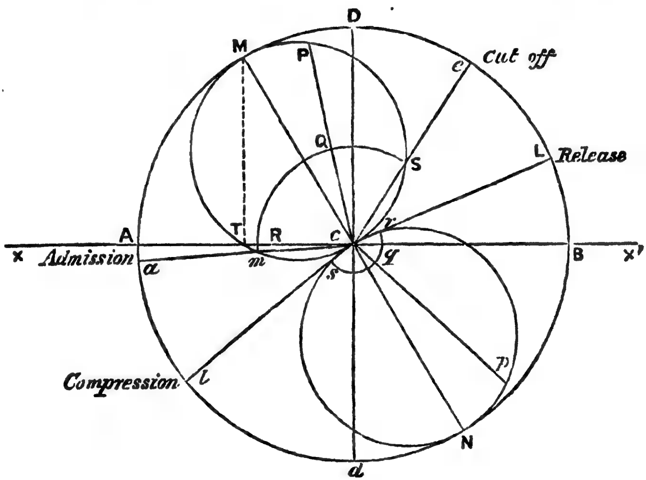

FIG. 155.

the angle M C D represents the angle by which the crank of the eccentric is advanced to allow for the lap and the lead.

Hence angle M C D = angle of advance.

Upon C M as diameter describe a circle which which will be one valve circle of the diagram.

With centre C and radius C R describe the circular arc *m* R S: Join C *m* and produce it to *a*; then *a* is the position of the main crank at admission. Also join C S and produce it to *e*; then *e* is the position of the crank at cut-off.

In like manner we may deal with the points of release and compression, and trace the period during which the exhaust of steam is continued.

For this purpose draw the second valve circle on C N, and with centre C and radius C r, equal to the inside lap, draw the circular arc $r q s$; then L is the position of the crank at release and l the same at compression.

The respective openings for steam and exhaust at any time are represented by lines such as P Q and $p q$. The steam port is always large enough to give the full opening as marked, but it often happens that the exhaust port is more contracted relatively, whereby the actual opening may be somewhat less than that set out in the diagram.

Ex. 1. If the travel of a slide be $4\frac{1}{2}$ inches, outside lap $=1$ inch, inside lap$=\frac{1}{4}$ inch, angle of advance$=30°$, find the positions of the crank at admission, cut-off, release, and compression.

Referring to diagram (1) in fig. 156, we have C D$=2\frac{1}{4}$ inches

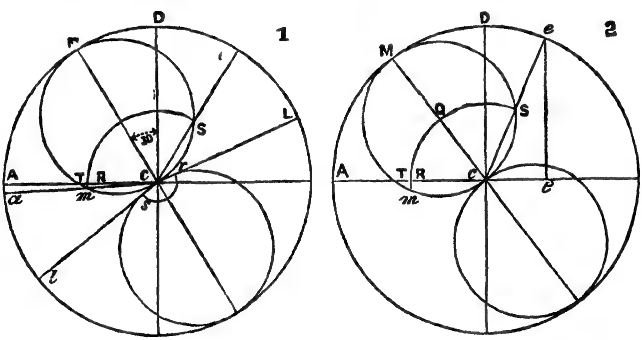

FIG. 156.

and angle M C D$=30°$, also C R$=1$ inch, whence the point m is found, and C m a, C S e can be drawn. Also C $r$$=\frac{1}{4}$ inch, whence C r L, C s l can be drawn, and it will be found that

$$\text{angle } ACa = 3° \ 36' \ 44'', \text{ angle } ACe = 123° \ 36' \ 44'',$$
$$\text{angle } ACL = 156° \ 22' \ 46'', \text{ angle } ACl = 36° \ 22' \ 46''.$$

Ex. 2. Given outside lap$=1$ inch, lead$=\frac{3}{16}$ inch, and greatest

opening of port to steam $=1\frac{1}{16}$ inch, show that angle of advance $=35° 9'$, travel of valve $=4\frac{1}{8}$ inches, and that cut-off takes place when crank has described an angle $115° 51'$, or at ·718 of stroke.

Referring to diagram (2), draw a valve circle whose diameter is $CQ + MQ = 1 + 1\frac{1}{16} = 2\frac{1}{16}$ inches.

With radius $CQ = 1$ inch describe the arc mQS.

Draw CRTA such that $RT = \frac{3}{16}$; then A is the position of the crank when on the line of centres.

Draw CD at right angles to CA; then MCD is the angle of advance $= 35° 9'$ by measurement.

Draw CS*e*, which gives *e*, the position of the crank at the point of compression, and if *et* be drawn perpendicular to AC produced we have $At =$ ·718 of the stroke, and angle $ACe = 115° 51'$.

Here it will be necessary to quit our subject for the present. The object of the writer has been to point out the influence which the modern theory of heat has exercised on the practical construction of the steam engine, and to contrast the views entertained under the old and new doctrines. No one can be said to have a knowledge of the principles of mechanics who has not grasped to some extent the philosophy of the dynamical theory of heat, and an endeavour has accordingly been made to put forward, in a simple manner, many elementary propositions which are essential for the comprehending of that ideal heat engine which an engineer should always keep in view as something to be aimed at though it can never be reached.

The mechanism and construction of the engine have been
important particulars ; the drawings have

Errata

Page 301, second and third lines of Example I., *for* inside *read* outside, and *for* outside *read* inside

Examples

inches, the angle of advance is 35°, the inside lap is $2\frac{1}{4}$ inches,
side lap is $\frac{1}{4}$ inch. Find greatest opening to steam, lead, and point of cut-off.

Ans. Greatest opening $= 2\frac{1}{8}$ inches; lead $= \frac{1}{4}$ inch; cut-off at $\frac{7}{10}$ of stroke.

Ex. 2. Given travel of valve = 5 inches, outside lap = $\frac{3}{4}$ inch, inside lap = $\frac{1}{8}$ inch, angle of advance = 20°, prove that the position of crank is at

admission	2°	30′	before line of centres
cut-off	142	30	after ,,
release	167	40	,, ,,
compression	332	20	,, ,,

Ex. 3. An engine has steam and exhaust ports each 3 inches wide, also inside lap = $\frac{1}{4}$ inch, outside lap = $\frac{3}{4}$ inch. Find travel of valve when the port just opens fully to exhaust; find also the angle of advance when lead = $\frac{1}{8}$ inch.

Ans. Travel = $6\frac{1}{2}$ inches; angle of advance = 15° 37′.

Ex. 4. Given width of steam port = 2·5, opening to steam = 1·5, outside lead = ·25, opening to exhaust = 2·5, travel of valve = 5, no inside lap, find outside lap and angle of advance, all the measurements being in inches.

Ans. Lap = 1 inch, angle of advance = 30°.

Ex. 5. Given travel of valve = 4 inches, angle of admission = $3\frac{1}{2}$°, cut-off at $\frac{5}{8}$ stroke, release at ·95 of stroke, prove that lead = $\frac{1}{10}$ inch, angle of advance = 39° 30′, outside lap = 1·176 inch, inside lap = ·4728 inch; also that

angle of crank at cut-off	= 104°	29′
,, ,, release	= 154	10
,, ,, compression	= 306	49

Ex. 6. Given travel of valve = 4 inches, outside lap = $1\frac{1}{8}$ inch, inside lap = $\frac{3}{8}$ inch, angle of advance = 40°, prove that lead = ·16 inch, also that

angle of crank at admission...	= 5° 46′,	period of stroke	= ·0025
,, ,, cut-off	= 105 46	,,	= ·6359
,, ,, release	= 150 48	,,	= ·9364
,, ,, compression	= 309 12	,,	= ·1839

Ex. 7. Given travel of valve = 4·6 inches, cut-off at $\frac{4}{5}$ of stroke, exhaust opens when piston is $\frac{1}{25}$ from end of stroke, angle of advance = 30°, prove that

outside lap = ·903 inch	outside lead = ·247 inch
inside lap = ·277 inch	inside lead = ·873 inch

Ex. 8. Given cut-off at $\frac{7}{10}$ stroke, outside lap = 1 inch, lead = $\frac{3}{16}$ inch, prove that angle of advance = 36° 35′ 21″, travel of valve = 4 inches.

Ex. 9. Given cut-off at ·6 of stroke, compression at ·85 of stroke, angle of admission = 4°, width of steam port = $1\frac{1}{4}$ inch, and greatest opening of steam ports = $\frac{3}{4}$ their area, prove that travel of valve = $4\frac{3}{4}$ inches, angle of advance = $41\frac{1}{4}$°, lead = ·128 inch, outside lap = 1·438 inch, inside lap = ·17 inch, angle of release = 143°, angle of compression = $45\frac{1}{2}$ or $134\frac{1}{2}$, period of stroke at release = ·9, period of stroke at admission = ·0013.

SUPPLEMENT

ON GAS ENGINES.

1. THERE are two numerical results connected with the theory of heat which are of the highest practical value. They are given in the Text Book, and are the following:—

(1) By an expenditure of 772 foot-pounds of mechanical work *one thermal unit* of heat is produced.

(2) In converting a quantity of heat into work the greatest amount of work which can by any possibility be obtained from a heat engine

$$= \frac{T - t}{T + 460} \times \text{total heat},$$

where T and t are the temperatures on Fahrenheit's scale between which the heat engine (supposed to be perfect) is working.

In applying these laws in the construction and management of heat engines, we begin by increasing the elasticity or pressure of a quantity of gas, such as air or steam, by heating it. Such heated gas is then passed into a cylinder and is expanded so as to do work. After a portion of its heat has been converted into work, the residue is expelled from the cylinder at a lower temperature.

The first operation, then, is to obtain a supply of heated gas, and here we encounter losses at every stage. Thus in burning coal for the generation of steam there is a continual escape of heat by reason of the imperfections of the furnace, and by the discharge of heated products up the chimney.

Again, there are difficulties to be overcome in forcing heat

through the shell of the boiler, and in conveying it into each individual particle of the water or steam.

It would appear then to be a manifest advantage if the heat could be applied directly to the elastic gas without the intervention of any furnace or boiler. An idea or suggestion so obvious as this can hardly have failed to attract those who are in search of improvements, and, accordingly, numerous attempts have been made from time to time, in order to obtain an elastic agent by setting fire to a mixture of coal gas and air within the very cylinder in which the piston of an engine is working. The neat developed in the gas during the act of burning would be thus compelled to supply a source of energy in the closest contact with the moving piece to which such energy is to be transferred.

No action can be more direct than this, and, in truth, it is the very thing which for centuries past has been done in a gun.

When gunpowder is fired in a closed chamber the temperature of the gases rises to a little above 2,000° C., and in the case of guncotton the temperature of the gases is about twice that of gunpowder (Noble).

The enclosed gases at these temperatures exert an enormous pressure, amounting in the case of guncotton of specific gravity ·55 to as much as 70 tons per square inch, whereas with gunpowder of specific gravity 1 and fired in a closed vessel, the pressure would reach 43 tons per square inch (Noble).

Pressures such as these, generated suddenly in a closed vessel, cannot be dealt with in the present state of our knowledge, except for the discharge of projectiles. They are not suitable for driving the piston of an engine.

In order to adapt heated gas to the performance of useful work in an engine, we require (1) that its pressure shall not rise too suddenly, (2) that the intensity of the pressure shall be kept within reasonable limits.

These conditions can be fulfilled during the burning of coal gas or of some form of carburetted hydrogen when mixed with air.

2. **Explosive mixtures of gas and air.**—Simple hydrogen explodes when mixed with oxygen in sufficient proportions. Thus

$$\left.\begin{array}{l}\text{2 volumes hydrogen}\\ \text{1 volume oxygen}\end{array}\right\}\begin{array}{c}\text{give a louder explosion than any other}\\ \text{proportionate admixture.}\end{array}$$

It is a fundamental fact in chemistry that water is composed of hydrogen and oxygen in the above proportion.

For the purposes of an engine coal gas or some form of carburetted hydrogen is preferable to pure hydrogen, and we may point out that, speaking generally, 100 volumes of coal gas contain

Hydrogen	50	volumes
Marsh gas	35	"
Carbonic oxide, Carbonic acid, Olefines, Nitrogen	15	"
Total	100	"

3. We now refer to experiments made in relation to the explosion of a mixture of marsh gas with air.

The substance *marsh gas* is carburetted hydrogen (CH_4) and it explodes when mixed with oxygen in sufficient quantity. The most violent detonation takes place when 1 volume of marsh gas is mixed with 2 volumes of oxygen. Thus—

$$CH_4 + 2O_2 = CO_2 + 2OH_2,$$

the result of the combustion is carbonic acid and water in the form of steam, and it is calculated that the pressure of the heated gases would rise to about 37 atmospheres.

Since *air* contains $\frac{1}{5}$ of its volume as pure oxygen, the marsh gas would require 10 volumes of air for perfect combustion, and there would be present 8 volumes of inert nitrogen, which would reduce the force of the explosion.

Thus with 1 volume of marsh gas and 10 volumes of air the pressure of explosion is estimated at about 14 atmospheres.

With a larger amount of air the explosion becomes weaker, and with 18 volumes of air the mixture does not explode at all, but burns with a pale blue flame round a taper immersed in it.

It is matter of interest to find out (1) when there is just enough air for an explosion, and (2) when an explosion is arrested by the presence of too large a quantity of air.

Experiments for ascertaining these limits were made in 1877 by Coquillon ('Journal Chem. Soc.' 1877, vol. i. p. 166), who tested mixtures of marsh gas and air with the following results :—

Marsh Gas Volume	Air Volume	
1	5	No explosion.
1	6	First limit of possible explosion.
1	7	Sharp explosion.
—	—	. . . . .
1	12	Explosion weaker.
1	14	Same.
1	15	Same.
1	16	Slight commotion, this being the last limit of explosion. The air is in excess.

Similar results had been previously obtained when coal gas was mixed with air. There are limits of explosion in both directions; with too little air the mixture will not explode, and the same thing happens when the air is in excess.

Thus Wagner found (1876) that ignition of a mixture of gas and air by means of an electric spark began at a proportion of mixture of 1 of gas to 5 of air, and ceased when the mixture was diluted in the proportion of 1 of gas to 13 of air. Ordinary illuminating gas requires for its complete combustion 6·3 volumes of air to 1 of gas.

4. **Pressures produced by the explosion of gas and air in a closed vessel.**—Another point of inquiry is to ascertain by experiment the extent to which the elastic pressure of a mixture of gas and air is increased when the combustion or explosion takes place in a closed vessel.

The first published experiments on this subject were made in 1861 by Hirn, who employed mixtures of hydrogen or coal gas with atmospheric air. The explosion vessels were cylindrical, one having a capacity of 3 litres and the other of 36 litres.[1] Taking a mixture of 1 volume of hydrogen with 9 volumes of air the pressure on explosion rose to 3·25 atmospheres, whereas the pressure, as given by calculation, would have been 5·8 atmospheres. The student will understand that the method of calculation is the following:—

Conceive that we select a definite mixture of hydrogen and air. The burning of the hydrogen will give out a certain number of thermal units, and the product of combustion will be steam,

[1] 1 litre = 61·024 cubic inches.

having a known specific heat and a known latent heat. The rise in temperature of the contents of the vessel consequent on the explosion may, therefore, be estimated; and from the rise in temperature the increase in pressure of the gaseous products can be inferred. This rise in pressure would then be contrasted with that actually recorded by a pressure gauge attached to the vessel.

Similar results were obtained with other mixtures of hydrogen and air, as well as with mixtures of coal gas and air. In all cases the observed pressures were much below those which theory would have led us to anticipate.

In 1866 Bunsen made experiments ('Phil. Mag.' 1867, vol. xxxiv. p. 489) wherein he used a very small explosion vessel, having a capacity of only a few cubic centimetres.[1] Also he passed the igniting spark through the whole length of the vessel in order to secure an instantaneous spread of the flame. His results supported those of Hirn, a similar difference between the calculated and observed pressures being established.

In 1880 there were again experiments by Mallard and Le Chatelier, giving a large difference between the calculated pressures and those actually obtained.

5. **Dugald Clerk's experiments.**—We pass on to the experiments of Dugald Clerk, whose paper on the subject is inserted in vol. lxxxv. of the 'Proceedings of Inst. Civ. Eng.' Here the mixtures of gas and air were exploded in a strong cast-iron cylinder, the internal space being 7 inches in diameter and $8\frac{1}{4}$ inches long. The explosion was produced by an electric spark, and the pressures were marked on the drum of a Richard's indicator, which was caused to revolve uniformly by a clock train driven by a falling weight, and regulated by a fly or fan.

The revolving drum was enamelled, and a soft black-lead pencil attached in the usual way to the parallel motion marked on the drum a line which recorded the movement of the indicator piston. Also the drum itself rotated uniformly at the rate of 1 revolution in ·3 of a second, and it followed that the position of a mark made by the pencil recorded also the time elapsed since the instant of explosion.

Great care was taken in charging the vessel, the volumes and

[1] 1 cubic centimetre = ·061024 cubic inch.

temperatures of the gas and air which were introduced being measured. The drum was then set in rotation, and, the spark being passed, a line was traced upon the drum which we propose now to examine.

It has been found that in different towns the quality of coal gas varies, and Mr. Clerk has been careful to distinguish the gas accordingly.

In this notice it will suffice to select a few prominent results as indicating the character of the curves.

Thus: Taking Glasgow coal gas and air.

Temperature before ignition = 18° C. Atmospheric pressure = 14·7 lbs.

Vol. Gas	Vol. Air	Greatest Pressure in pounds per sq. inch above Atmosphere	Time elapsed after Passage of Spark
(*a*) 1	7	89 lbs.	·07 second
(*b*) 1	11	63 lbs.	·18 second
(*c*) 1	13	52 lbs.	·28 second

The curves corresponding to (*a*) (*b*) (*c*) are given below, and marked on the diagram.

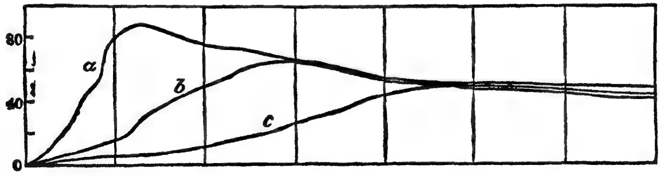

Fig. 1.

The gradual falling off in pressure, as shown by the curves, indicates the loss of elasticity due to the passage of heat through the walls of the cylinder.

It is important to observe that in curve (*a*) the pressure rises rapidly to the full intensity, and then falls gradually by reason of the cooling action of the surface of the cylinder.

Whereas in (*b*) the pressure reaches its greatest value more

slowly and is sustained for some little time before it begins to diminish sensibly in intensity.

The same thing is shown in (*c*), and the explanation probably is that the complete combustion of the gas is retarded by the presence of an additional quantity of air.

As before stated, a pressure curve, such as that under discussion, shows different results with the gas supplied in different towns.

The practical point for consideration is, what proportion of air will give the best working pressure, and Mr. Clerk's deduction from these experiments is that with Glasgow coal gas the most economical mixture would be 1 gas to 11 air, while with Oldham coal gas he would prefer to use 1 gas to 12 air.

6. When hydrogen takes the place of coal gas and the mixture is strong in gas, the explosion is so sudden and the rise of pressure so rapid that the effect produced is that of a blow.

Taking 2 volumes of hydrogen and 5 volumes of air, where the air contains just enough oxygen to combine completely with the hydrogen, the pressure rose to its greatest amount in $\frac{1}{100}$th of a second. An action of this kind is unsuitable for the purposes of an engine.

It further appears from Mr. Clerk's experiments that when hydrogen is diluted with air in larger quantity the pressure rises less rapidly and becomes quite manageable, but it is less in amount than in the case of coal gas, and hydrogen is not at all a good gas to employ in an engine.

7. **Comparison between early and modern rifled guns.**—It is interesting to note that the same principle of sustained pressure and less rapid action which has obtained in gas engines has been applied in parallel lines to the modern rifled gun.

If gunpowder be exploded in a closed vessel and pressure gauges be provided to indicate the tension of the gas, we find :

(1) The same reduction of pressure from the cooling effect of the vessel.

(2) The outline of the pressure curve varies considerably with different kinds of powder.

That is to say, there may be a rapid rise of pressure to a great

height, the gas being formed suddenly and brought at once to the highest limit of pressure, or the pressure may, as it were, rise gradually, and be sustained for some little time at or near its greatest value, which is less in amount than when the rise in pressure occupied a shorter period.

The improvements made in modern artillery have been based upon these observations, and a comparison of the old and modern systems will be readily presented to the eye in the form of a diagram, where (A) represents the outline of a 25-ton gun as it would have been made some 10 or 15 years ago, and (B) is the outline of the same 25-ton gun as it is now made, the bore of (A) being 12 inches, and that of (B) being 10 inches.

We are here quoting from a lecture given by Captain Noble at the Institution of Civil Engineers in 1884.

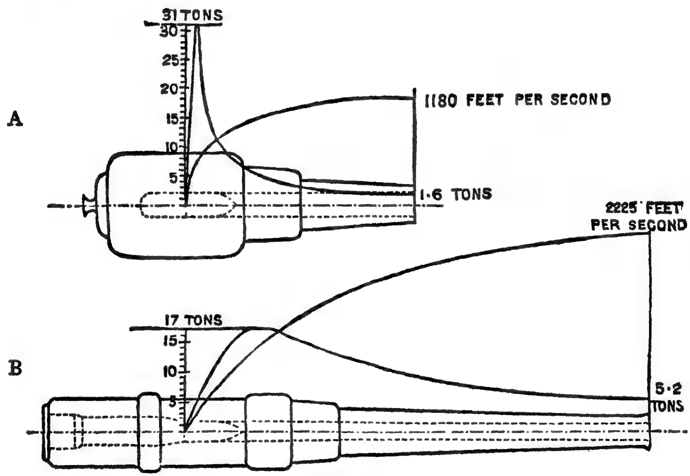

FIG. 2.

Upon each figure is drawn a pressure curve, the starting-point being the base of the projectile before firing, as shown in dotted lines, the vertical line indicating pressures, and the horizontal line giving the position of the projectile for each pressure.

There is also a curve of velocities, showing the velocity generated in the projectile during each instant of the motion.

Taking gun (A), it appears that the pressure rises rapidly to 31 tons per square inch, and falls along the expansion curve to 1·6 ton. This is analogous to the explosion of hydrogen in a gas engine.

The velocity generated is 1,180 feet per second. Gun (A) is not a breech loader, and on account of the sudden rise of pressure it becomes necessary to increase the thickness of the metal enormously around the powder chamber.

In gun (B) (which is a breech loader) the pressure rises only to 17 tons per square inch, and falls to 5·2 tons, but the rise is more gradual, and the intensity is sustained as shown by the curve. Also the gun is much longer, whereby the velocity generated rises to no less than 2,225 feet per second, which is nearly twice its former amount.

Of course the velocity impressed is the important thing aimed at, as every student of mechanics will understand; and here again we have an analogy to the modern gas engine, where coal gas is selected in preference to hydrogen, and air is mixed to nearly the full extent which is practicable in order that the combustion may be less rapid and the pressure more sustained.

It appears that about twenty-five years ago our most powerful piece of artillery was a 68-pounder, throwing its projectile with a velocity of 1,570 feet per second (Noble), whereas now the weight of our guns is increased from 5 tons to 100 tons, and the projectile from 68 lbs. to 2,000 lbs., the velocities from 1,600 feet to 2,000 feet, and the energies from 1,100 foot-tons to 52,000 foot-tons (Noble).

8. **The Lenoir engine.**—A patent for the Lenoir gas engine was applied for on February 8, 1860, No. 335, by *J. H. Johnson*, being a communication from abroad by *J. J. E. Lenoir*, of Paris.

The specification stated:—'This invention consists in the application and use of an inflammable gas mixed with a proper proportion of atmospheric air and ignited inside a cylinder by the aid of electricity; the expansion thereby produced acting upon the piston and imparting motion thereto, which motion may be transmitted in any convenient and well-known manner to a driving shaft.' Then it described the arrangement of insulated platinum wires, in connection with a battery, and so disposed that an

electric spark was produced at the right instant at either end of the cylinder, whereby the mixture of gas and air was fired.

Subsequently the lighting was effected by a jet of gas and a slide conveying a small flame of gas into the cylinder.

A general idea of the arrangement of the working parts will be obtained from the annexed diagram, where C B is the cylinder of the engine, P the piston, P Q the piston rod, A R the crank, R Q the connecting rod, and F the fly wheel.

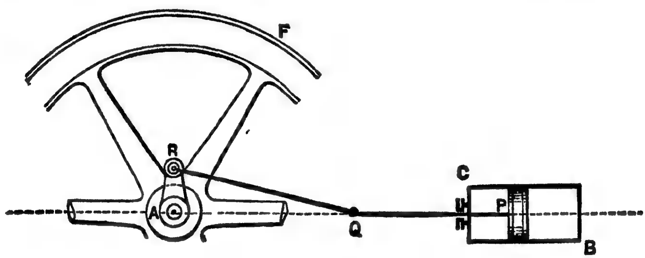

FIG. 3.

The actual working of the engine may be understood by comparing together the remaining diagrams. Fig. 4 shows a horizontal longitudinal section through the axis of the cylinder, and also gives a vertical cross section through the cylinder.

As the cylinder when at work attains a considerable temperature, it is surrounded by a water jacket, shown in both sections, through which a supply of water is constantly circulating.

The slide L M regulates the admission of air and gas into the cylinder, while the slide N T is concerned only with the exhaust of the waste products of combustion. These slides are pressed against the faces of the cylinder by springs not shown in the drawing.

It will be observed that there is a gas inlet terminating in two forked branches *r* and *s*, which lead into gas orifices marked *o*, *b*.

There is also an air inlet *p*, communicating with the space A, which would form the exhaust passage in an ordinary steam cylinder, but is here applied for supplying air to the cylinder. The pipe *p* is covered, as shown, by a head or cap *b*, which forms a sort of gasometer, and retains some gas which would otherwise

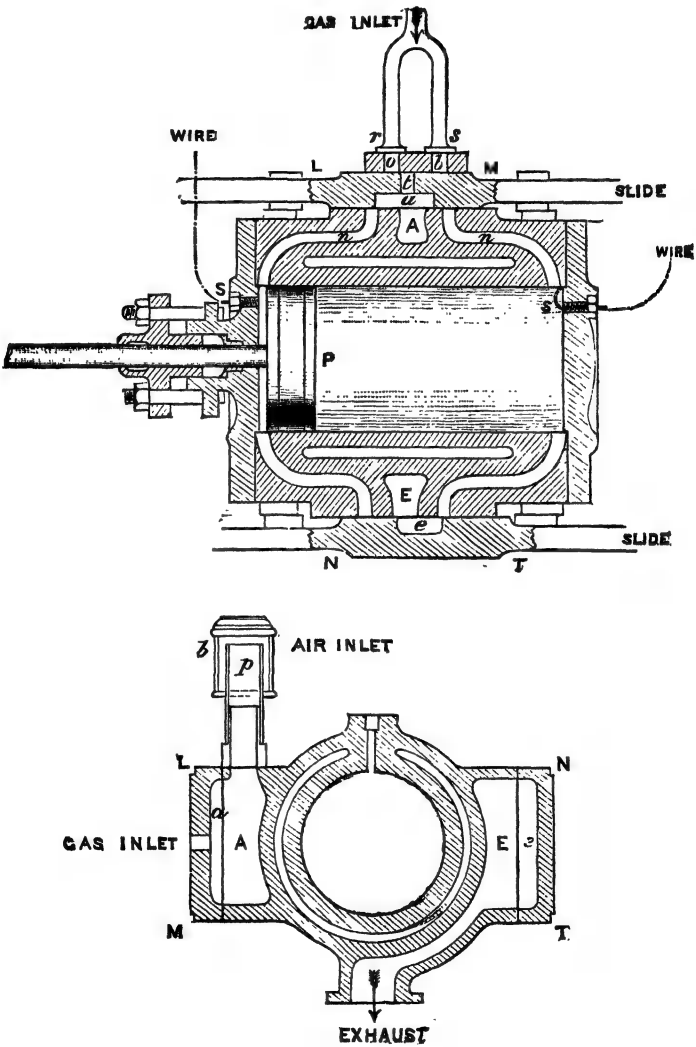
GAS INLET
WIRE
r
s
o
l
t
u
L
M
SLIDE
A
n
n
WIRE
S
S
P
E
e
SLIDE
N
T
b
p
AIR INLET
L
N
a
GAS INLET
A
E
M
T
EXHAUST

FIG. 4.

escape and which is drawn into the cylinder at the next stroke of the piston.

The mode of working the engine is the following: The piston travels a certain distance along the cylinder by reason of its connection with the crank and fly wheel, and in doing so acts as a pump to draw in a charge of air and gas at a pressure equal to that of the atmosphere. When the piston has performed about half its stroke, the charge is fired by the electric spark, and the stroke is then completed under the pressure of the enclosed gases. On the return of the piston the waste products in the cylinder are expelled into the open air.

The patentee states that the slide L M opens the passage *n* to air entering from A, just before *t* comes into communication with the gas inlet *o*. Thus air enters first of all, and then comes gas and air which 'both enter the cylinder but without becoming entirely mixed together, and will exist in the space behind the piston in distinct strata.' This is what is said, but it would be rather difficult to prove it, and in this treatise no attempt will be made to deal with the subject of stratification of the charge, even if there be such a thing. The slide now closes the passage *n*, when an electric spark sets fire to the mixture, and the piston is driven to the end of its stroke.

The products of combustion are got rid of by the slide N T working over the exhaust passage E. The manner in which this is done is precisely the same as in an ordinary steam engine, as will be apparent from the drawing, and it is therefore unnecessary to describe it.

Towards the end of the specification we find the following passage:—'The object of introducing a supply of air into the cylinder before the gas is allowed to enter is to neutralise the effect of the carbonic acid gas formed by the combustion of the inflammable gas, as the carbonic acid gas without being thus neutralised might prevent the ignition of the remainder of the inflammable gas.'

9. Some indicator diagrams taken from an early Lenoir engine are to be found in vol. 51 of 3rd series, 'Journal of the Franklin Institute.' One of the curves is set out in the diagram, which, however, is imperfect, inasmuch as no scale of pressures is given.

The atmospheric line is marked A B, and shows the stroke of the piston. The charge is drawn in at the atmospheric pressure, but the pressure of the mixture of gas and air falls to 11 lbs. above a vacuum or zero line just before explosion. It then rises in a steep, inclined line to 48 lbs., and the rest of the diagram tells its own tale.

It is stated that the crank shaft makes 50 revolutions per

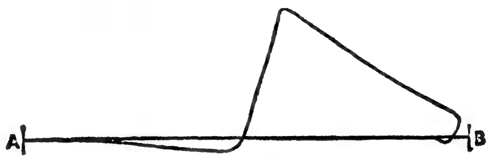

FIG. 5.

minute, that the cylinder is 8⅝ inches in diameter, the stroke of the piston being 16¼ inches, and that engines of this type are sold at from ½ to 4 H.P.

10. **The Otto and Langen atmospheric gas engine** is an engine of which large numbers were at one time made both in England and Germany, and which attracted a good deal of attention from the undoubted success with which it worked. It was the subject of a patent of 1866, No. 434, to *C. D. Abel.* In 1875 Mr. Crossley, of Manchester, read a paper before the Institution of Mechanical Engineers, wherein he described the construction of the engine and the manner in which it operated.

No doubt there were many valuable points about it, but being in truth, as its name implies, an atmospheric engine—that is, an engine with an *open* cylinder in which the piston is driven up by the pressure resulting from the explosion of a mixture of gas and air, and driven down by the pressure of the atmosphere, it is rather difficult, when the principles of the theory of heat have received full recognition, to understand how such an engine could continue for any length of time to occupy the first place.

It is rather unsafe to state positively the lines in which mechanical improvement will advance, and it happened that Mr. Crossley, in the paper referred to, adduced a variety of reasons to show that engines of the Lenoir type, in which a mixture of gas

and air contained in a cylinder delivers its energy after combustion in driving a piston connected with a crank and fly wheel

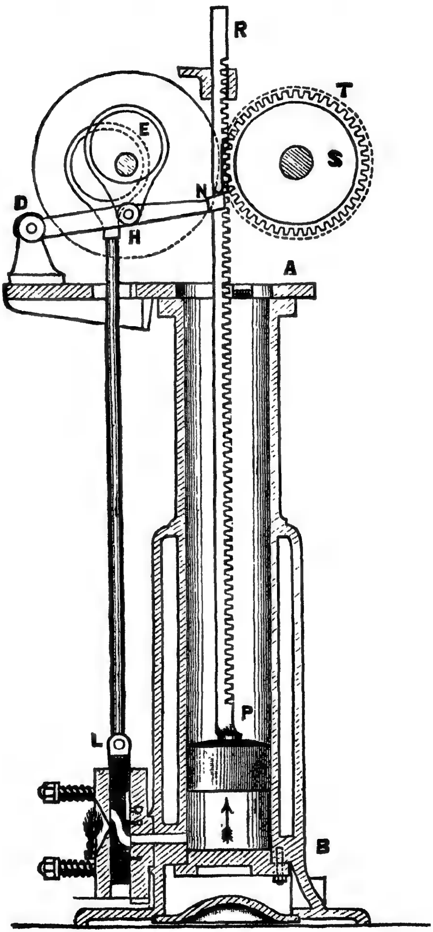

FIG. 6.

after the manner of an ordinary steam engine, were wrong in

principle and could never succeed because the effect is that of a blow and is not a sustained pressure.

Then the argument advanced was that the Otto and Langen engine worked on the only true principle, viz. that of sustained pressure, and it did so in the following manner. The piston in an open cylinder is provided with a piston rod in the form of a rack. The piston is raised about $\frac{1}{11}$ of the stroke, and sucks in an explosive mixture. The charge is then fired, the engine being really a gun which stands vertically with open mouth pointing upwards, the explosive compound of gas and air taking the place of a charge of powder, while the piston represents the shot. The piston is free during its ascent—that is, it does not drive any of the mechanism of the engine, and the charge is not sufficient to force the piston out of the gun, but only to send it close up to the open end.

After explosion a partial vacuum is formed beneath the piston, which descends under the superior pressure of the atmosphere, the rack on the piston rod being now suddenly caused, by the operation of a friction clutch, to impart a sustained driving pressure to the fly-wheel shaft.

It is not the purpose of the writer to describe this engine with particularity, but only to give a general idea of its action.

The diagram shows the piston P, provided with a piston rod P R in the form of a rack, and working in the vertical open-mouthed cylinder A B, which has a water jacket as shown.

It should be understood that S is the main shaft of the engine, and that although P R is always in gear with a spur wheel T riding on the shaft S, yet there is inside that wheel, and not shown in the drawing, a friction clutch whereby T runs loose on the shaft S during the whole upstroke of the piston, but is locked thereto during the whole of the downstroke. In other words, the piston is *free* during its ascent, but is a working piston during its descent.

In the diagram the piston has been raised through about $\frac{1}{11}$ of the stroke, and has sucked in a charge of gas and air which is on the point of being fired by the slide L.

The piston is raised through this space by the lever D H N, operated by an eccentric E H on the shaft E which is driven by spur wheels from the main shaft S. The end N of the lever D N,

whose fulcrum is at D, actuates a tappet at N upon the rod P R, and leaves P R free to ascend after the explosion.

On the shaft E is a second eccentric, working the slide L by means of the rod shown in the diagram.

These eccentrics, which are made fast to each other, are carried loose upon the shaft E, and are started and stopped as required by an arrangement of a ratchet wheel and catch or paul not shown in the drawing. A movement of the eccentrics takes place when it is wanted, and not otherwise.

Outside the slide a small gas jet is kept burning, by means of which gas fed into a chamber in the valve is ignited, and at the right moment the opening of the chamber to the outside is cut off, and the flame therein is brought opposite the entrance to the cylinder and explodes the charge.

The piston being then driven to the top of its stroke, and the wheel T being, during this time, in effect an idle wheel, it will be found that the products formed within the cylinder by the burning of the gas rapidly fall in pressure.

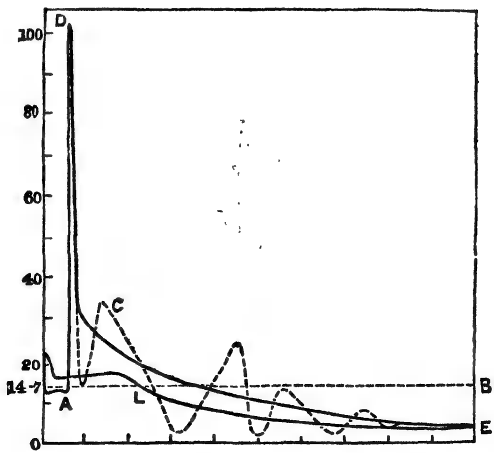

FIG. 7.

11. The action within the cylinder will be made clear by an indicator diagram, which shows a sudden upward jump of the

pencil at the instant of explosion, and then a series of oscillations, given in dotted lines, from which the mean curve of pressure, viz. D E, is deduced. It thus appears that the pressure within the cylinder falls to 11 lbs. per square inch below the atmosphere when the piston reaches the top of its stroke, and that the driving pressure in the return or working stroke, as recorded by E L, varies from 11 lbs. per square inch below the atmosphere to the atmospheric pressure itself, at about $\frac{4}{5}$ of the stroke, as shown by the position of L. It averages 9 lbs. during the time of action, and on the whole there is a mean of about 7 lbs. per square inch effective pressure during the period when the piston rack is driving the mechanism.

It is admitted that engines of this type are necessarily limited to a small power, and Mr. Crossley stated that no attempt had been made to increase their size beyond that of a 3-horse-power engine.

12. **The Otto gas engine.**—We have now to describe the Otto engine, as made by Crossley Brothers, which has established the efficiency and economy of gas engines.

This invention was the subject of a patent granted in 1876, No. 2,081, to *C. D. Abel* for 'improvements in gas motor engines' (a communication from abroad by *N. A. Otto*).

The specification states that in gas engines, as previously constructed, an explosive mixture of combustible gas and air was introduced into the cylinder and ignited, whereby there resulted a sudden expansion of the gases, and a development of heat, a great portion of which was lost by absorption. According to the present invention, a combustible mixture of gas or petroleum vapour and air is introduced into the cylinder, together with air in such a manner that the particles of the combustible mixture are more or less dispersed in an isolated condition in the air, so that, on ignition, instead of an explosion ensuing, the flame will be communicated gradually from one combustible particle to another, thereby effecting a gradual development of heat, and a corresponding gradual expansion of the gases.

A drawing showed the cylinder and piston in section, together with a slide for the admission of gas and air. The piston on moving outwards from the bottom of the cylinder drew in air for a certain

space. It then moved an additional space and drew in combustible gas and air. The whole contents of the cylinder were at atmospheric pressure as in the Lenoir engine. The charge was then fired by the action of a small external gas flame, and the piston was driven to the end of its stroke. On the return of the piston the products of combustion were expelled into the atmosphere and the operation was repeated as before.

Then the patentee observes that, by this mode of operating, any shock which would result from sudden explosion is avoided, partly through the dispersion of the combustible charge, and partly because the first admitted charge of air which does not become completely mixed with the combustible charge acts as a cushion between this and the piston, and owing to the gradual development of heat and expansion of the gases there is comparatively little loss of useful effect.

Engines operating in this manner might be single acting, the return stroke being effected by the momentum of the fly wheel, or they might be double acting, a charge being introduced at each end of the cylinder.

If the invention had remained at this stage it is probable that it would have attracted little attention, but the specification goes on to describe another and a different mode of working the engine which is of the highest possible value, and which forms, as the writer thinks, the real improvement disclosed in the specification. After a statement that the engine might operate with the gases at atmospheric pressure or compressed in any desired degree, there follows a description and drawing substantially the same as that annexed.

In this case the piston does not come close up to the cylinder-cover on its return after ignition, as in the engine first referred to, but a considerable space is left at the end of the cylinder which becomes filled with the residue of the products of combustion at about atmospheric pressure. As soon as the piston begins its forward stroke, air is drawn in, and afterwards gas and air. On the return of the piston the whole contents of the cylinder are *compressed into the space at the end*, and the charge is then fired. The expansion drives the piston to the other end of the cylinder, then follows the exhaust, and the cycle of operations is repeated.

Referring to the drawing, the piston P is connected with a crank shaft, and the space between the dotted lines *a*, *d*, is the length of stroke.

C is a passage for the entrance of the charge, while *e* is an exhaust passage, leading in another direction, for the escape of the waste products of combustion. C *a* is a considerable space or

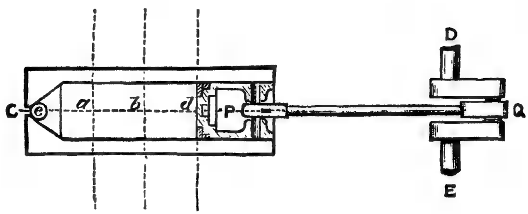

FIG. 8.

clearance which is filled with the products of combustion at about atmospheric pressure when we commence to trace the working of the engine. The piston is driven by the fly wheel except during that particular stroke when there is explosion, and we propose to trace the operation of four strokes.

(1) As the piston travels from *a* to the position marked by the dotted line *b*, air is drawn in, then follows a mixed charge of gas and air till the piston arrives at *d*.

(2) As the piston returns from *d* to *a* the charge is compressed into the space C *a*, and may attain a pressure of (say) 40 lbs. on the square inch.

(3) The charge is fired by a gas flame and drives the piston from *a* to *d*.

(4) The piston returns from *d* to *a*, and expels part of the products of combustion through E, leaving the space C *a* filled with the residue at about atmospheric pressure.

The cycle of four strokes is then repeated, the piston being driven onwards always at the third stroke.

The question arises, what is the new principle, or new idea, here developed? No doubt it consists in the peculiar cycle of operations. Up to this time gas engines were worked by drawing in the charge during the first portion of a stroke and then firing

it. Now, for the first time, the charge was drawn in at the first stroke, it was compressed at the second stroke, it was fired at the third stroke, and the residue was expelled at the fourth stroke.

This method of working was new and original, but it was also founded on true mechanical principles, and formed an excellent illustration of a useful application of the law of inertia of matter. Suppose we have a small heavy wheel mounted on bearings with its axis horizontal. It will be easy to keep it revolving by a series of pushes or impulses with the open hand. In doing so, as the wheel revolves faster and faster, each impulse may recur at longer intervals, and the speed of rotation may nevertheless continue to be nearly uniform.

So with the gas engine. The fly wheel of a small engine makes (perhaps) 180 revolutions per minute, at which speed the impulse of the burning gas may be given at intervals, but the rotation of the fly wheel may continue to be nearly uniform. We rely upon the inertia of matter to help us.

13. But not only is the mode of working practicable when looking at the question from a mechanical point of view, but there is also the direct and positive gain of dealing with a charge of compressed gas and air instead of a mixture at or about the atmospheric pressure. The engine acts as its own compressing pump. To start at the instant of explosion with the compressed contents of a whole cylinder full of gas and air instead of the uncompressed contents of half a cylinder, is an advantage pretty evident to ordinary apprehension, and which may be made more clear by calculation.

Then also it is claimed that the residue of unburnt products remaining in the cylinder will act as a cushion to moderate the effect of the explosion upon the working piston.

14. Having described in general terms the Otto engine as specified, we pass on to give a particular account, with diagrams, of an Otto engine of half horse-power, recently furnished by Messrs. Crossley to the Normal School of Science as an example of the type of engine which they recommend at the present time.

It will be convenient to commence with an explanation of the method of charging the cylinder with gas and air, then to discuss the arrangement for firing the charge, as well as the

method of getting rid of the waste products. Finally, the comparative position of the slide and piston will be shown, the action of the governor will be explained, and a general view of the engine will conclude this notice.

15. **Charging with gas and air.**—As in the gas engine last described, a slide is employed for charging the cylinder and also for conveying a flame to the charge. Such a slide is a flat plate of metal, having certain passages, straight or curved, which are so different from anything seen in a steam engine, that considerable attention is necessary before the action of the slide will be understood.

The annexed diagram shows a horizontal section through the cylinder with the piston P at the end of the stroke. The space

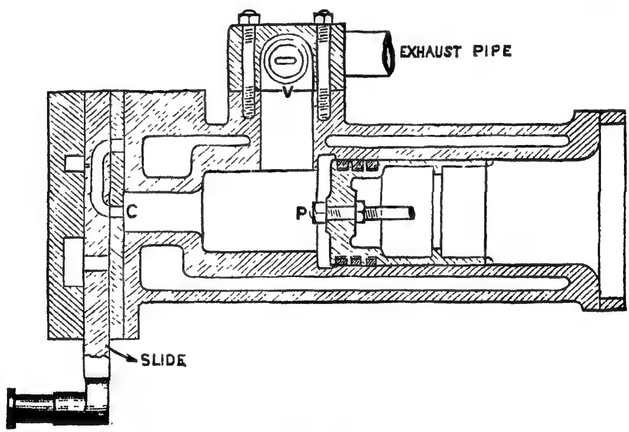

FIG. 9.

C P is that portion of one end of the cylinder in which the charge is compressed and corresponds to C *a* in fig. 8. There is also a horizontal side passage terminating in a valve V, which leads to an exhaust pipe through which the waste products are discharged.

At the end, C, of the cylinder are three plates, the first marked *inner cover* as being nearest to the cylinder, the second being the slide itself, and the third being the *outer* cover. These plates are

shown separately in a perspective view, in order that the student may form a better idea of their appearance.

The slide is faced on both sides and moves to and fro between the fixed covers, being operated by an eccentric as in a steam engine, but with this important difference, that the slide moves *once* to and fro while the crank shaft makes *two* complete revolutions. In other words, the slide makes two strokes while the piston makes four strokes.

The general arrangement of the working parts being thus made apparent, we have to point out that the slide has to fulfil two functions, viz. (1) the charging, (2) the lighting, and since it is arranged that one-half of the slide is concerned in the first operation, and the other half in the second, it becomes convenient to discuss each operation separately.

We refer now to fig. 10, which shows the slide and its covers fitted together, and fig. 11 gives other views in which each cover is placed at an angle to that face of the slide with which it is usually in contact, the object being to indicate the various openings and passages made in and through the slide and covers.

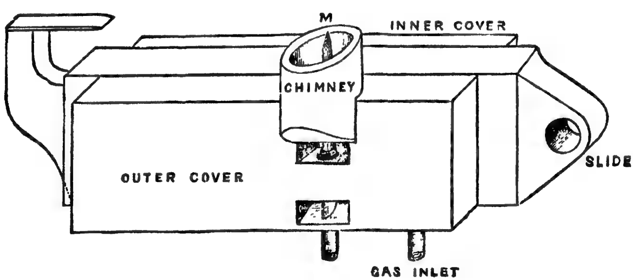

FIG. 10.

It appears that there are three principal openings in the inner cover, viz. (1) the gas inlet B, (2) the air inlet D, (3) the port opening to the cylinder, marked C; and inasmuch as it is necessary to charge the cylinder with both gas and air, it is obvious that passages must be contrived for conveying gas from B to C, and air from D to C.

We pass on to the sectional drawings, but the student should

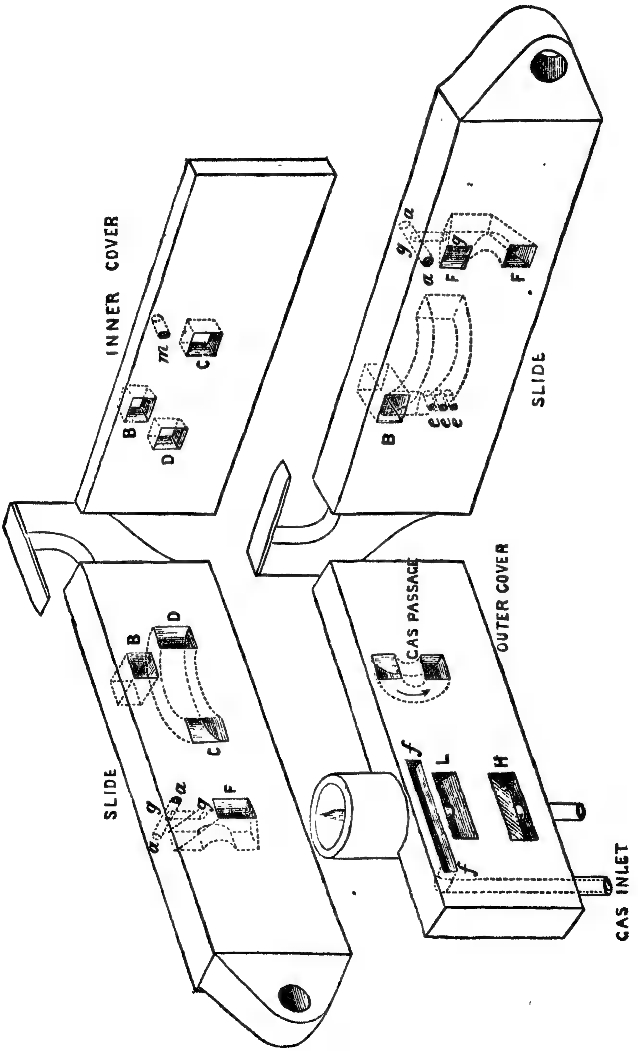

FIG. 11

continually turn back to fig. 11 in order to trace the operation as completely as if he had the slide and covers before him.

In fig. 12, (1) shows a vertical transverse section of the slide and covers taken through the gas inlet B. Within the material of the outer cover, which is a thick plate of metal, there is a curved passage R having two openings on the face of the cover. The bend R communicates by small ducts or perforations marked *e*, with another passage A, shown in section, which leads immediately to C. The object of these perforations is to check or throttle the flow of gas, and to prevent it from entering the cylinder too rapidly.

The gas having entered A, passes directly from thence to the cylinder, and at the same time becomes mixed with air. To make this clear we refer to fig. 12 (2), which is a horizontal section

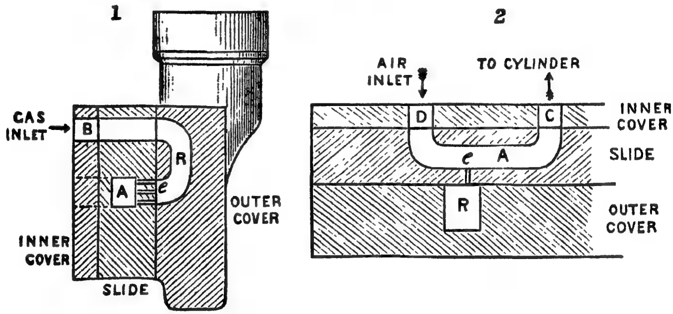

FIG. 12.

through the slide and covers taken on the level of C, the opening to the cylinder. Within the material of the slide is a curved passage D A C, having openings at D and C. The port D is the *air inlet*, and when the slide is in the position shown, there is a free passage of air into the cylinder. At the same time, gas entering A by the perforations *e* can pass directly to C.

In the Otto engine supplied by Messrs. Crossley to the Normal School, which is of half horse-power, there is no provision for admitting *first* a supply of air to the cylinder, and *secondly* a supply of mixed gas and air. On the contrary, the gas and air are admitted together from the commencement, and it is during the last part

of the admission that the charge becomes richer in gas, the object no doubt being to obtain a more combustible mixture at that end of the cylinder where the combustion flame enters.

In the annexed diagram three positions of the slide are given.

In (3) the slide is moving to the right and is about to open simultaneously both D and R to C.

In (4) the perforations *e* have come opposite the chamber R, also D is fully open to C, and the result is that gas and air are both drawn into the cylinder.

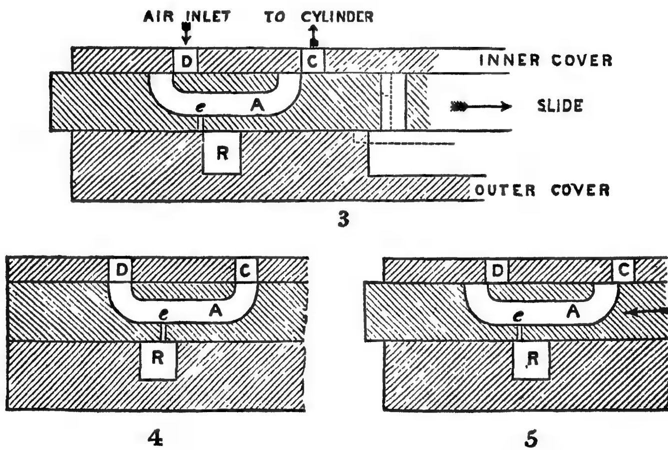

FIG. 13.

In (5) the slide now moves to the left, whereby the passage D becomes contracted, while *e* remains fully open. Hence the supply of air falls off, and the last mixture drawn into the cylinder becomes richer in gas, and therefore better adapted for accepting and carrying on the flame of ignition which lights the charge.

16. **Firing the charge.**—We proceed to describe the method of firing the charge in the cylinder, and refer to fig. 14, which gives a vertical transverse section through the slide and covers, and should be compared with the complete drawing in fig. 11.

The chimney M is shown in section, and at the base thereof is

a small jet of gas J, kept constantly burning, and called the *slide light.*

The slide is at one end of its stroke, and has the forked passage F in such a position that the lower branch of the fork is opposite to the air passage H, and the upper branch communicates with the base of the chimney.

It is to be noted that the single opening F, in which the forked passage terminates, is on a level with C, the opening into the cylinder.

On the side of the outer cover is a passage marked *f*, the general arrangement of which is better seen in fig. 11. This passage is freely open to a supply of gas passing along a pipe marked '*gas inlet*,' the object being to keep *ff* filled with gas, and ready to supply the chamber F, so as to support a flame of gas burning therein.

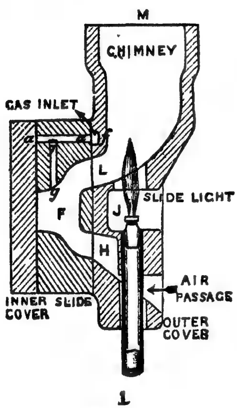

FIG. 14.

The passage marked *a a g g*, formed by the meeting of two cylindrical passages *a a*, *g g*, performs a double office, as will be explained hereafter. At present we regard it as allowing gas to pass freely from the gas inlet *f* to the interior of the chamber F.

The gas, on entering F, is carried by the draught of the chimney to the lighted flame, or slide light J, and begins to burn, air being constantly supplied from below at H, whereby the chamber F is filled with the flame of lighted gas.

The gas, filling F, is readily lighted when the slide is in the position shown, and the object will be to keep the flame alight. In order to do so it will be necessary to supply F with both gas and air up to the last moment before the ignition of the charge.

The annexed diagrams, marked (2) (3) (4), are horizontal sections through the slide and covers, taken on the level of the lower edge of the opening C.

In (2) the cylinder is receiving its charge, while F is becoming filled with the flame of burning gas.

It is particularly important to note the position of the passage *a a* with reference to the passage *ff*. Both these passages are shown by dotted lines, because they do not appear in the section, by reason of their lying on a different level, but they play their part notwithstanding.

Also (2) shows that *a a* is open to *ff*, which means that gas is entering F freely.

In (3) *a a* has just passed beyond *ff*, at which time no more gas can enter F, and the flame within that chamber would soon die

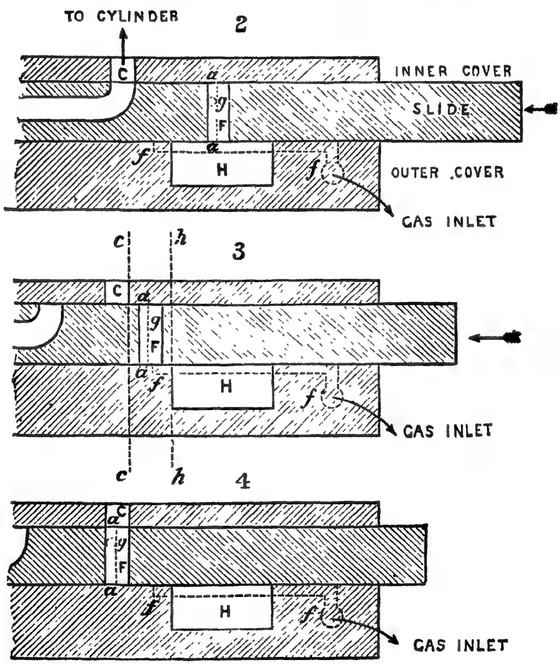

FIG. 15.

out; it will, however, keep burning during the brief interval occupied in carrying F across the space marked by the dotted lines *c c* and *h h*, after which F opens to C and the charge takes fire.

In (4) the passage F is fully open to C, and the slide is at the end of its motion towards the left-hand side of the diagram.

The diagrams (5) and (6) serve to explain a matter of considerable importance.

On turning back to fig. 11 the student will observe a small hole or perforation in the inner cover marked *m*, and the question would be asked, what is the object of this perforation? Upon careful examination it appears that the opening *m* is continued through the cover and leads direct into the cylinder. It, therefore, forms a small aperture into the cylinder, and is ordinarily closed by the face of the slide.

But *m* is on a level with *a a*, and in one position of the slide it will lead directly from the interior of the cylinder to *a a*.

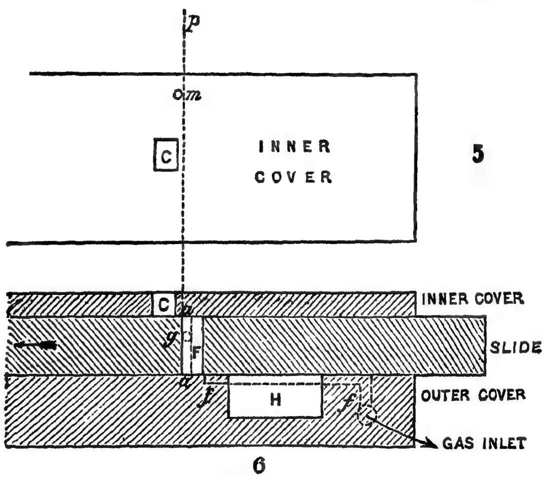

FIG. 16.

(5) shows an elevation of the inner cover, and (6) is a sectional drawing corresponding to (3).

In the state of things shown in (5) and (6) the passage *m* is just on the point of opening into *a a*, and it will do so before the edge of F passes the edge of C.

At this time the burning mixture of gas and air in F is at the

pressure of the atmosphere, while the charge in the cylinder is probably at about 40 lbs. pressure. It follows that if F were opened directly to C the sudden pressure of the gases in the cylinder would drive the flame back from the opening, and the lighting of the charge might fail.

But, according to the arrangement under discussion, *m* opens to *a a* before F opens to C, and as a consequence thereof the pressure of the contents of F is brought up to 40 lbs. by the entrance of gas and air from the cylinder, first through the passage *m* into *a a*, and then through *g g* into F. The result is that at the instant when the full opening is made from F into C there is an equilibrium of pressure in both F and C, and the lighting of the charge is safely carried out.

17. **The exhaust.**—It has been explained that upon each alternate return stroke of the piston an exhaust valve is opened which allows the greater part of the waste products to escape into the atmosphere, but leaves a residue in the end of the cylinder.

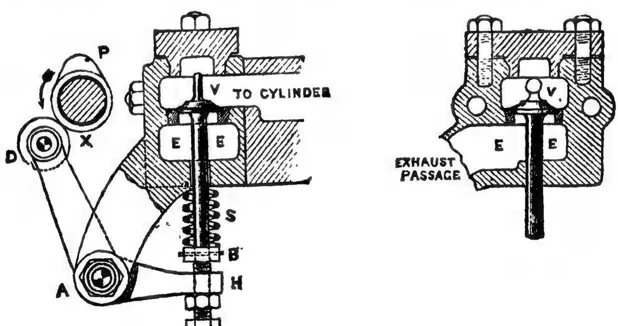

FIG. 17.

An exhaust valve, marked V, is indicated in fig. 9, and we have now to describe its operation and the method of working it. It will be remembered that the exhaust takes place through a branch passage leading out at right angles to the axis of the cylinder.

The annexed drawings show two vertical sections through the valve V, that on the right being parallel to the axis of the cylinder, and the other being transverse to it.

The valve V has a spindle V B provided with a collar at B, which is attached to the spindle by means of a pin. A spring S abuts against B at one end, and against the valve casing at the other end, and retains the valve closed except when B is lifted by external pressure.

In order to lift the valve a cam P, keyed upon the shaft X, depresses the end D of a bell crank lever D A H, and thereby raises the end H of the arm A H. As soon as the cam P has passed under the roller D the elasticity of the spring comes into play, and the valve is closed, as shown in the sketch.

18. **Regulator for supply of gas.**—The pendulum governor of Watt is applied to the regulation of the engine, but its action is different from that in a steam engine, inasmuch as its function is not to control the rate of supply of gas by opening a valve in a greater or less degree, but simply to determine whether the cylinder shall receive a fresh charge, or whether for one or more complete double revolutions of the fly wheel the charge of gas shall be entirely cut off.

The drawing is taken from an end view of the engine, showing the slide in position as worked by a slide rod attached to a crank pin E at the end of a revolving shaft. The gas supply comes through a pipe on the right hand, provided with a stopcock, and having a valve V, closed by a spring, which controls the admission into the cylinder. The governor balls act upon a sleeve connected with the short arm of the lever A C D, whose fulcrum is at C, and which is provided with a vertical rod D T, hinged at D, and carrying a projecting piece marked T. On the slide is another projection, marked S, and when S and T are opposite each other it is apparent that a sufficient movement of the slide to the right hand will cause S to strike against T, and to push it to the right, thereby opening the valve V, and allowing the charge of gas to enter the slide, and so to pass on to the cylinder.

When the engine is at full work this would happen at every alternate forward stroke of the piston, and if the speed is accelerated, so that the balls rise higher, the end A of the lever A C D rises also, whereby T is depressed below S, and no gas is admitted into the cylinder.

When the rate of revolution of the balls returns to the normal

state, it is apparent that T will come opposite to S, and that a mixed charge of gas and air will again be drawn into the cylinder.

If T were allowed to rise above S, there is nothing to bring it down again, and the engine would stop.

The cone on the top of the governor is a load which rests on a shoulder upon the spindle. The slowest working-rate of the engine would just suffice to bring the sleeve in contact with the

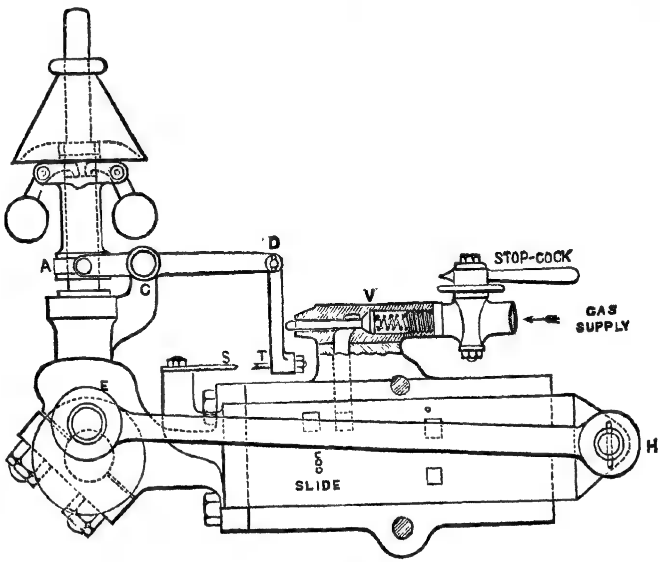

FIG. 18.

base of the cone, in which case the stop S would be exactly opposite to T.

If the balls tended to open still further, they could only do so by raising the heavy cone, and it follows that a considerable rate of increase in the speed of the engine will be necessary before T can be lowered sufficiently to fall below S, or before the supply of gas is cut off.

There are thus two rates of speed between which the engine

can work in the usual manner. If the highest limit be exceeded, the cone is raised and the gas cut off, which soon brings down the rate, whereupon the supply of gas is automatically renewed. But there is no automatic recovery at any speed below the lower limit, or the engine will not work at less than a definite rate determined beforehand by the position of the governor balls.

19. **Working of the engine.**—The annexed diagram taken from the gas engine under consideration is intended to show the positions of the piston and crank at certain periods of the working, and at the same time to record the corresponding positions of the slide.

Taking the diagrams in regular order, we find in (1) that the slide is just about to admit the mixed charge of gas and air into the cylinder, the piston being near the end of its stroke, and the crank about to pass a dead point. This state of things is marked *charging begins.*

In (2), the crank is proceeding onwards, the charging is in full operation, and the slide is admitting the charge of gas and air freely into the cylinder.

In (3), the crank has passed the dead centre and the piston is beginning to return, whereupon the slide diagram shows that the end of the cylinder is closed and that compression has begun. At the same time the slide is beginning to assume the position necessary for firing the charges.

In (4), the slide has arrived at the point of its stroke where firing begins, and it will be seen that the piston is just approaching the final limit of its movement towards the left hand, the space into which the compressed charge of gas and air is forced just before the instant of firing being indicated by the hollow spaces under the word *compression.*

In (5), the mouth of the cylinder is again closed and the charge pent up becomes expanded and heated so as to urge the piston onwards and cause it to complete the working stroke. When the piston arrives at the position shown in the sketch, the exhaust valve commences to open, as may be clearly seen by inspecting the indicator diagram given in a subsequent article.

20. **Plan view of the Otto engine.**—The annexed full-page diagram presents a general view of the complete engine now

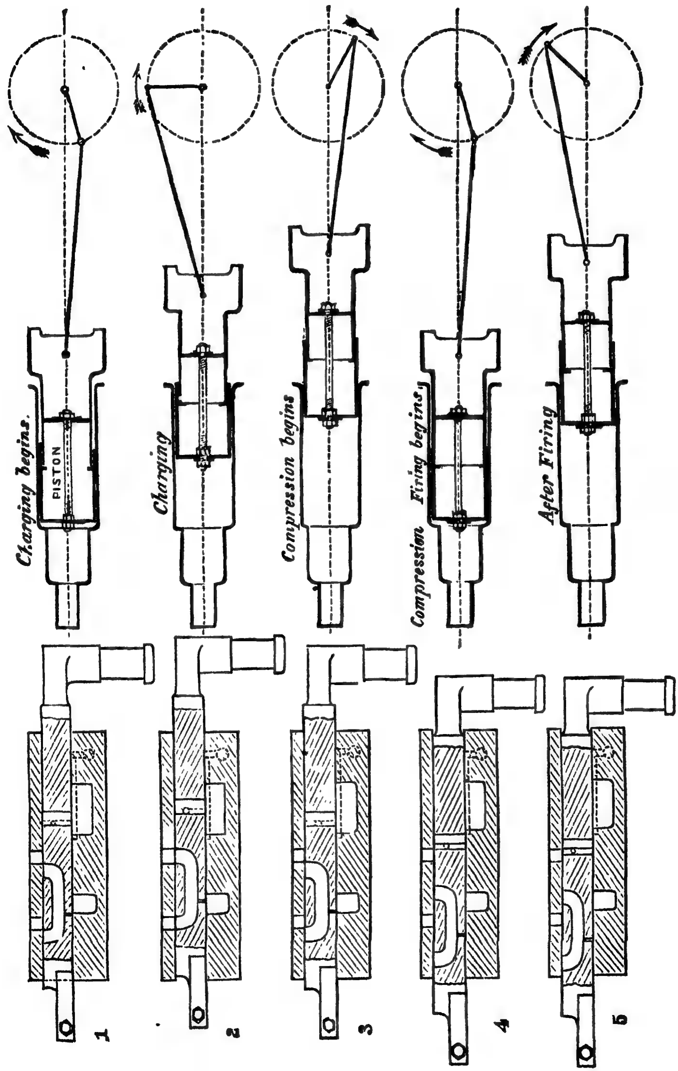
Charging begins.
PISTON
Charging
Compression begins
Compression
Firing begins.
After Firing
1
2
3
4
5

FIG. 19.

under examination, which is technically an engine of $\frac{1}{2}$ H.P., and which may, as stated in a circular by the makers, be enlarged up

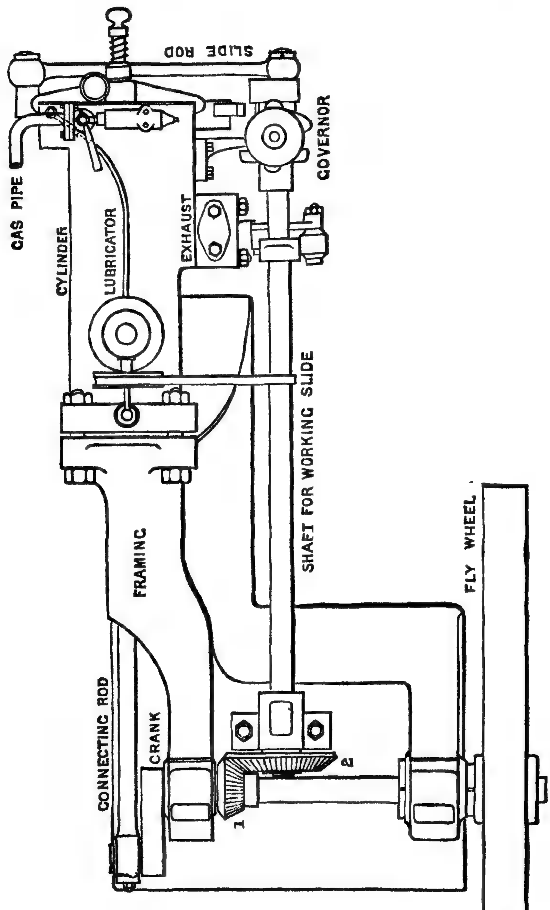

FIG. 20.

to 12 H.P. Twin cylinder engines of the same type are also furnished which indicate 40 H.P.

We are now referring to a plan view of the engine, which shows a horizontal cylinder attached to a framing and having a crank and connecting rod together with a crank shaft and fly wheel arranged as indicated.

It appears from the previous drawings that the piston is a hollow trunk having guides of some length, and linked to the crank by a connecting rod as in an ordinary trunk engine.

The crank shaft carries a driving wheel marked (1) gearing with another bevel wheel marked (2) having double the number of teeth. This latter wheel is keyed to a shaft for working the slide, the object being to reduce the motion of the slide relatively to that of the piston and to cause the slide to make only two strokes while the piston makes four strokes. This reduction of motion is a fundamental characteristic of the Otto engine.

The slide is actuated by a slide rod shown in the diagram, one end of the rod being attached to a pin, placed eccentrically on the end of the driving shaft.

The position of the exhaust valve is also marked, as well as the position of the governor, and the mechanism for operating the exhaust valve is indicated. There is a lubricator, having a mechanical feed for distributing oil to the slide and working parts. The lubricator is kept working by a small strap running upon the shaft used for working the slide, and there is a gaspipe shown for admitting a supply of gas to the slide and cylinder; a pipe for circulating water would appear in the drawing, but this, together with other minor fittings, has been omitted in pursuance of the intention to give a general conception of the arrangements and principal working parts of the engine.

21. **Indicator diagram of the Otto engine.**—The drawing is a copy of an indicator diagram taken from the engine already described.

The atmospheric line, which is also the line of volumes, is marked C B, and it is apparent that the volume of the clearance is represented approximately by the distance between the vertical line marked *ignition* and the line of pressures C D. The horizontal full line therefore represents the stroke of the piston, which is 9 inches.

The charge of gas and air is drawn in at atmospheric pressure

by the forward stroke of the piston ; it is then compressed to about 35 lbs. above the atmosphere, as shown by the line B E. At this point ignition takes place, whereby the pressure is carried up to 150 lbs., the behaviour of the gases during expansion being shown by the line marked *expansion*, the rapid slope at the end indicating that the exhaust valve has begun to open.

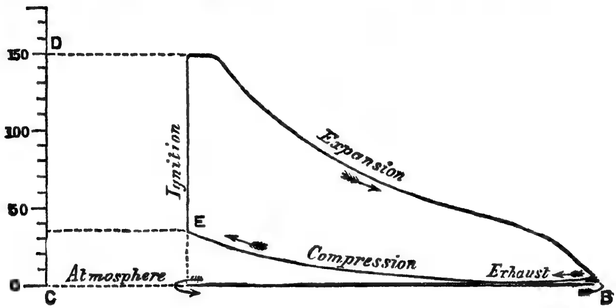

FIG. 21.

Then comes the exhaust at atmospheric pressure, whereby the indicator pencil runs along the horizontal line and returns again, retaking in a fresh charge as shown by the arrow vertically under the point E.

While this card was being taken the fly wheel was making 180 revolutions per minute, and the length of stroke of the piston being, as stated, equal to 9 inches, and the diameter of the cylinder being $4\frac{1}{2}$ inches, it is easy to calculate the indicated horse-power from the diagram.

This has been done, and it appears that the mean effective pressure on the piston$=60{\cdot}975$ lbs.

$$\text{Hence I.H.P.} = \frac{60{\cdot}975 \times \frac{\pi}{4}(4\frac{1}{2})^2 \times \frac{9}{12} \times \frac{180}{2}}{33{,}000} = 1{\cdot}98$$

$$= 2 \text{ H.P. very nearly.}$$

22. **Fittings of the engine.**—There are certain fittings which we proceed to describe by reference to the engine of $\frac{1}{2}$ H.P. Taking, first, the supply of gas, it will be found that precautions are necessary in order to prevent the disturbance produced by successive explosions from extinguishing or making unsteady other

lights in the building which are fed from the same pipe as that which supplies the engine when at work.

For this purpose the gas passes through a regulator valve and a gas bag before it reaches the engine. If it be desired to measure the quantity of gas consumed, a meter may be placed between the main pipe and the regulating valve. A ⅝-inch pipe will suffice for the engine, and a small pipe with two branches may feed the slide light and the passage marked *gas inlet* in fig. 11, the function of the latter inlet being to supply *f f* with gas.

Another fitting is an *air valve*, which is a cylindrical box, open at the base, 7 inches in diameter and 8 inches long, terminating in a neck leading to the air inlet in the inner cover marked D in the drawings. The cylinder is divided by five transverse plates having 1¼-inch holes alternately in the top and bottom of each plate.

There is also the *exhaust pipe*, which is 1½ inches in diameter, and passes first into a strong cast-iron cylinder 5½ inches in diameter and 16 inches long, after which it leads on to a cylindrical box 10 inches in diameter and 14 inches deep, filled with beads or small pebbles, whereby the noise caused by the escaping gases is reduced as much as possible. The jacket surrounding the cylinder must be supplied with *circulating water*, which is here provided by a ¾-inch pipe and regulating tap, the escape pipe being the same size as that for the supply.

The *starting* of the engine is a simple matter. The sleeve of the governor is raised and supported by a catch, the object being to bring T opposite to S in order that the cylinder may take in a charge of gas together with air. The gas is turned fully on, the slide light is set burning, and three or four rapid turns are given to the fly wheel, which are generally enough to commence an action in the cylinder and to start the engine.

APPENDIX.

QUESTIONS AND EXAMPLES, CHIEFLY NUMERICAL, TAKEN FROM THE SCIENCE AND ART EXAMINATION PAPERS.

1. A steam engine at the mouth of a coal pit is employed in compressing air to a density of four atmospheres, this compressed air at once acquires a high temperature, and for convenience is cooled with water down to 60° ; it is then conveyed in a pipe to the bottom of a pit and along one quarter of a mile horizontally, where it is set to work an engine similar to the ordinary non-condensing engine; the air when liberated produces a freezing atmosphere all round. Will you explain the above by referring to natural laws? (Science Exam. 1869).
2. What are the chief constituents of coal, and their average relative proportions, for which the engineer has to provide in the construction of furnaces? Draw a comparison between what the engineer has to do, as compared with the gas-maker, in the using of coal. (1869.)
3. What is meant by capacity for heat? The capacity for heat of mercury is ·033 ; how much, at the temperature of 240°, will be sufficient to raise 12 lbs. of water from 50° to 58°? (1867.)
4. Define the *duty* of a steam engine. What is the duty of an engine which burns 2·2 lbs. of coal per indicated horse-power per hour? (1874.)
5. How has the work done in raising the temperature of a pound of water through one degree been ascertained? A pound of coal gives out during combustion 12,000 units of heat; how much work in foot-pounds could be done by burning a pound of coal if there were no waste? (1873.)
6. If steam were admitted into a cylinder at a pressure of 15 lbs. and a temperature 212° F., and were expanded to a temperature of

100° F., what is the greatest amount of work which could be done according to theory? Prove the formula. (1878.)

7. An air engine takes in heat at a temperature of 300° F., and gives out heat at a temperature of 50° F.; find theoretically the amount of work which it could do if certain conditions were capable of being realized. State these conditions, and draw the indicator diagram of the engine. (1877.)

8. A steam engine of the beam order of construction, having the steam cylinder at one end of the beam and a lifting pump at the other end, the pump being 24 inches in diameter, is employed in pumping water from a dock to a height of 50 feet, the performance of this duty requiring the whole power of the engine. Circumstances have arisen that require the engine to raise water 200 feet, and a smaller pump has been placed in the centre between the fulcrum of the beam and the original pump, so arranged that either pump may be used as required; what should be the size of the new pump so as to make available the full power of the engine? (1872.)

9. Water has to be raised from a mine at two different levels, namely, fifty and eighty fathoms; from the former thirty cubic feet, and from the latter fifteen cubic feet per minute. What power of steam machinery will be required, assuming the modulus of the plant to be $\frac{8}{10}$? (1872.

10. Obtain a formula for determining the weight of water which must be mixed with a given weight of steam, in order that the mixture may be reduced to water of a given temperature. What weight of water at 60° F. must be mixed with 20 lbs. of steam, at atmospheric pressure, in order to produce water at 120° F.? (1868.)

The formula is obtained as follows:—

Let x lbs. of steam at a temperature t be injected into y lbs. of water at a temperature t', and let the resulting temperature of the condensed steam and water be T. Also let H be the number of units of heat in steam at a temperature t, reckoning from zero of the Fahrenheit scale.

Then the steam loses $x\,(\mathrm{H}-\mathrm{T})$ units of heat, and the water gains $y\,(\mathrm{T}-t')$ units of heat.

$$\therefore x\,(\mathrm{H}-\mathrm{T}) = y\,(\mathrm{T}-t').$$

Ex. Here $x=20$, $t=212$, $\mathrm{T}=120$, $\mathrm{H}=1178{\cdot}6$, $t'=60$,

$$\therefore y\,(120-60) = 20\,(1058{\cdot}6). \quad \therefore y = 352{\cdot}87 \text{ lbs.}$$

11. Describe the arrangement of the condenser and air-pump of a condensing engine, and the valves connected therewith. The temperature of the injection-water is 60°, the steam enters the

condenser at a temperature of 212°; the water pumped out of the condenser is at a temperature of 110°; what weight of injection-water must be supplied for each pound of steam which enters the condenser? (The latent heat of steam at 212° is 966·6.) (1870.)

12. How much water should you allow for the condensation of each cubic foot of steam at 212° during the working of an engine? What quantity of water is required to obtain one cubic foot of steam at 212°? (1876.)

13. A pound of steam at 212° F. is passed into 20 lbs. of water at 70° F., what is the temperature of the water at the close of the operation? (1878.)

14. If a pound of water at 212° be mixed with x pounds of water at 60°, what is the value of x when the resulting temperature is 100°? Again, if a pound of steam at 212° be mixed with y pounds of water at 60°, find y when the resulting temperature is 100°. Account for the difference between x and y. (1876.)

15. A jet of steam at 210° F. is passed into an open beaker containing a strong solution of a salt (say nitrate of soda) in water. The solution presently boils; its temperature is then tested by a thermometer, and found to be several degrees above the temperature of the steam which heated it. Account for this fact. (1874.)

16. The degree of saltness of the water entering the boiler is read off as $\frac{1}{33}$, and that of the water in the boiler is kept at $\frac{2}{33}$; the temperature of the feed-water is 100°, and that of the water in the boiler is 248°; what percentage of the total heat given to the boiler is wasted by blowing off? (The total heat of steam at 248° is 1189·4.) (1870.)

17. Describe the safety valve. If a circular inch be allowed on the area of a safety valve for every 20 square feet of heating surface, what must be the diameter of a valve for a boiler whose heating surface is 1,200 square feet? (1868.)

18. The steam cylinder of a trunk engine is 60 inches in diameter, and the trunk is 24 inches in diameter. What is the diameter of an ordinary steam cylinder of the same effective area? (1872.)

19. A safety-valve has an area of 5 square inches, and is intended to open when the steam has a pressure of 60 lbs. per square inch. Make a pen-and-ink sketch of such a safety-valve, use a lever to hold it down, place a weight on the end of the lever in the proper position, give the length of the lever from the fulcrum to the centre of valve, and to the centre of the weight; give the weight in pounds. Work the question out in arithmetic. (1870.)

20. The area of a piston is 4,476 square inches, and the diameter of the piston rod is $\frac{1}{8}$th that of the piston : find it. (1868.)

21. The crank of a steam engine is 2 feet long, and the mean tangential force acting upon it is 17,000 lbs. What is the mean pressure of the steam upon the piston of the engine during each stroke? (1876.)

22. Show, with a sketch, the method of fitting a safety-valve to a locomotive boiler. The safety-valve is 5 inches in diameter, and the bearing faces are inclined at 45° to the axis of the valve. What should be the lift, in order that the available opening for the escape of steam may be $\frac{7}{10}$ of a square inch? (1870.)

23. The stroke of the piston of an engine is 24 inches, and the diameter of the driving wheel is 8 feet; what is the mean velocity of the piston when the engine is running at 40 miles an hour? (1872.)

24. The safety-valve on the boiler of a locomotive is held down by a lever and spring; sketch the arrangement. A safety-valve, 4 inches in diameter, is constructed so that each pound of additional pressure per square inch on the valve corresponds to 1 lb. pressure on the spring. What are the relative distances of the spring and valve from the fulcrum of the lever? After the valve is set, how much additional pressure per square inch will be necessary in order to lift it $\frac{1}{20}$th of an inch, the spring requiring 10 lbs. to extend it 1 inch? 1871.)

25. In a direct-acting horizontal engine the lengths of the crank and connecting rod are 1 and 5 feet respectively. How far is the piston from the middle of its stroke when the crank is vertical? (1875.)

26. A surface condenser consists of 1,000 brass tubes each, 6 feet long, and $\frac{3}{4}$ inch outside diameter. What amount of cooling surface does this give? Supposing that such a surface condenser is to be fitted to an engine, what pumps, valves, &c., would be required? (1875.)

27. A safety-valve is $2\frac{1}{2}$ inches diameter on the steam side, the lever is $17\frac{1}{2}$ inches long, and the distance from the fulcrum to the valve is $3\frac{1}{2}$ inches. What weight should be hung at the end of the lever in order that the steam may blow off at 30 lbs. pressure? (1875.)

28. Explain the importance of balancing the cranks in a locomotive engine. The leading wheel of an engine is $3\frac{1}{2}$ feet in diameter; what would be the pull on the centre of the wheel caused by an unbalanced weight of 9 lbs. upon the rim when the engine was running at 50 miles an hour? (1870.)

29. In the old-fashioned wagon boiler a vertical open tube, called a stand-pipe, passed through the shell of the boiler, and dipped below the surface of the water inside. If the steam pressure inside the boiler were 4 lbs. per square inch, at what height would the water stand in the pipe? (1870.)

30. A cylindrical boiler, with flat ends, is 30 feet long, 6 feet in diameter, and has two internal flues, each $2\frac{1}{4}$ feet in diameter. The pressure of the steam in the boiler is 40 lbs. on the inch; what is the whole pressure on the internal surface, in tons? How is the strength of a cylindrical boiler related to its diameter, the material being unchanged? (1870.)

31. In a direct-acting engine the diameter of the cylinder is 17 inches, and the mean pressure of the steam is 60 lbs., the crank being 12 inches long: what is the mean pressure on the crank in the direction of its motion? (1878.)

32. Taking a direct-acting engine, and disregarding the effect of obliquity of the connecting rod, you are required to assign the proportion of lap to the travel of the slide valve, in order to cut off steam at $\frac{3}{4}$ of the stroke. (1878.)

33. Give a description of the reverse-valve. If kept in its place by a weight of brass, what must be its thickness that it may be opened when the pressure of steam within the boiler is $1\frac{3}{4}$ lbs. below the atmosphere? The weight of a cubic foot of brass is 525 lbs. (1868.)

34. The mean steam pressure on a piston being 26 lbs. above the atmosphere, and the mean vacuum pressure 13·5 lbs., what is the force exerted on a piston of 63 inches in diameter, and what would have been the force if the engine had worked without condensation of steam? (1866.)

35. The crank of an engine is 3 feet 6 inches, and the connecting rod 9 feet long. Find the angle which the crank will make with the vertical when the engine is at half-stroke. (1866.)

36. The pressure of steam upon a piston is 40 lbs. per square inch, the resistance from imperfect condensation is 3 lbs. per square inch, the length of stroke is 10 feet, and the steam is cut off at $\frac{1}{5}$ of the stroke. Calculate the number of units of work done upon each square inch of the piston, and give the numerical result (log. 5 being 1·60944). Find also the load per square inch, and the position of the piston when the velocity is greatest. (1876.)

37. Describe an equilibrium valve. The upper side of an equilibrium valve is 9 inches in diameter, and the lower side 8 inches; find the power necessary to lift it when the pressure of steam is 16

lbs. above that of the atmosphere if the space between the upper and lower valves be a vacuum. (1867.)

38. What is a circular inch? A safety valve 7 inches in diameter is loaded to 6 lbs. on the square inch: what would be the load on each circular inch? (1867.)

39. Describe and explain some form of equilibrium valve. The diameter of a steam pipe is $12\frac{1}{2}$ inches, the upper and lower discs of an equilibrium valve being 12 and $10\frac{1}{2}$ inches in diameter respectively; what will be the lift of the valve when the pipe is fully open? (1869.)

40. Draw a section of a safety valve, loaded directly, and without a lever. The diameter of the valve being 4 inches, what should be the total load for blowing off steam at 75 lbs. actual pressure. (1877.)

41. Assume that the beam of a steam engine weighs 5 tons, the piston and piston rod 1 ton, the connecting rod 2 tons, and that the radius of the beam is $12\frac{1}{2}$ feet, that the length of stroke is 5 feet, and that the engine makes 30 revolutions per minute. The question is: What expenditure of mechanical power has to be incurred in overcoming the inertia of those parts due to the reciprocation and changing from rest to motion and from motion to rest? (1873.)

42. The initial pressure of steam in a cylinder, whose stroke is 5 feet 4 inches, is 45 lbs., and expansion commences when 2 feet 3 inches have been performed; find the pressure at the end of the stroke. Find also the horse-power, if the area of the cylinder is 2,218 square inches, and the number of strokes per minute 30. (1868.)

43. Describe a condenser gauge of an engine. The mean pressure on a piston being 12 lbs. above that of the atmosphere, and the mean vacuum pressure 13 lbs., what is the force exerted on a piston of 58 inches diameter, and what would have been the force had the engine worked without condensation of steam? (1868.)

44. Show how to find the work done by a crank. What force applied to the extremity of a crank at right angles to it will do the same work as a mean pressure of 4 tons acting on a piston throughout the up and down stroke? (1868.)

45. The cylinder of an engine is 74 inches in diameter, and the stroke is $7\frac{1}{2}$ feet; what is the capacity of the cylinder? How many pounds of water must be evaporated in order to fill such a cylinder with steam at an actual pressure of 15 lbs., it being given

that steam at 15 lbs. pressure occupies a space equal to 1,670 times that of the water from which it is generated? (1871.)

46. The internal edge of the seat of a conical valve is 5 inches in diameter, the vertical angle of the cone being 90°; what lift of the valve would give 1 square inch area of opening? (1876.)

47. A steam engine is employed to work two pumps alternately, giving out its full power in each case. The area of the plunger of the one pump is A, and it lifts water 50 feet, the travel of the plunger being x feet. Whereas the plunger of the second pump traverses $\frac{2x}{3}$ feet at each stroke, and lifts water 150 feet, what should be its area? (1876.)

48. The cylinder of an engine is 3 feet 6 inches in diameter, the stroke is 5 feet, and the steam is cut off at $\frac{1}{3}$ of the stroke. If steam be admitted into the cylinder at 45 lbs. pressure, find the work done in one stroke (log. $3 = 1{\cdot}0986$). (1876.)

49. The stroke of a piston is 5 feet, and the cylinder is 4 feet in diameter, steam is admitted at 20 lbs. pressure and is cut off at half stroke, find the work done. If steam be cut off at $\frac{1}{3}$ of the stroke, and the final pressure is required to remain unchanged, what should be the diameter of the cylinder in order that the work done may also remain unchanged? (log. $2 = {\cdot}6931472$, log. $3 = 1{\cdot}0986124$). (1875.)

50. The cylinder of a steam engine is 3 feet 6 inches in diameter, the length of stroke is 5 feet, and the crank makes 30 revolutions per minute; what is the horse-power of the engine, the mean effective pressure of the steam in the cylinder being 10 lbs. on the square inch above that of the atmosphere? (1876.)

51. Investigate an expression for the work done when steam is cut off before the end of a stroke. Steam at a pressure of 60 lbs. is admitted into a cylinder, and cut off at $\frac{1}{6}$ of the stroke; what should be the area of the piston in order that a weight of 30 tons may be lifted through the length of stroke? Allow for friction and back pressure. (log. $6 = 1{\cdot}792$.) (1874.)

52. In a compound cylinder marine engine, the diameter of the high-pressure cylinder is 57 inches, and that of the low-pressure cylinder is 100 inches, the stroke of each piston being $2\frac{3}{4}$ feet. The mean pressures of the steam in the respective cylinders are 26 lbs. and $8\frac{1}{2}$ lbs., and indicated horse-power is 1,028; find the number of revolutions made in one minute. (1875.)

53. The diameter of a steam cylinder in a single-acting condensing engine is 4 feet. The engine does the work of raising water to a height of 125 feet, by a pump 17 inches in diameter. What

should be the mean pressure of the steam on the piston, allowing what you think reasonable for loss by friction and back pressure? (The weight of a cubic foot of water is 62·5 lbs.) (1875.)

54. Steam is admitted into a cylinder at atmospheric pressure (say 15 lbs.) and is cut off at $\frac{1}{4}$ of the stroke. Find the steam pressure when $\frac{17}{20}$ of the stroke has been completed. (1878.)

55. Steam is admitted into a cylinder at atmospheric pressure, and is cut off at half-stroke. Divide the stroke into 20 equal parts, and suppose that the pressure at the beginning of each of these portions remains uniform until the piston reaches the next in order: find the whole work done during the stroke, it being given that the area of the piston is 200 square inches, the length of stroke 40 inches, and that 15 lbs. represents the atmospheric pressure.

(1878.)

56. In an expanding and condensing engine the pressure of steam on the piston at the commencement of the stroke is taken at 15 lbs. actual pressure, the steam is cut off at ·4 of the stroke and the back pressure is 4 lbs. on the square inch. The volume of the steam compared with that of the water is taken as 1,665, find the average pressure of the steam on the piston, and the number of cubic feet of water required per horse-power per hour. Given: log. 2 = ·6931472, log. 5 = 1·6094379. Diameter of cylinder = 2 feet; length of stroke = 2 feet 6 inches; number of revolutions per minute = 30. (1877.)

57. Two horizontal steam engines develop the same power and have each a 5 feet stroke. The cylinder of the one engine is 3 feet 6 inches in diameter, working with a steam pressure of 45 lbs. per square inch through the whole length of the stroke. The other engine is worked by the same initial pressure of steam, cut off at $\frac{1}{2}$ stroke.

The question is: What would be the relative maximum strain upon the crank pin, and also what kind of crank shaft would be required for each engine, assuming the breaking strength to be six times the working load and the material to be wrought iron of average quality? (1873.)

58. A steam engine is employed to drive machinery by means of a fly-wheel, having teeth on its rim, and gearing with a pinion on the line of shafting. Why is this a good arrangement? The fly-wheel is 15 feet in diameter, and the crank which drives it is 2 feet long. If the mean tangential pressure on the crank pin is 16,450 lbs., what will be the driving pressure on the pitch circle of the pinion? (1874.)

59. It is recorded of one of the earliest steam engines that it raised $18\frac{3}{4}$ cubic feet of water through a height of 19 feet at each stroke, and made $7\frac{1}{4}$ strokes per minute. The consumption of coal was 32 cwt. in 24 hours. Find the number of units of work obtained by burning 112 lbs. of coal. (The weight of a cubic foot of water is $62\frac{1}{2}$ lbs.) (1878.)

60. A crank 2 feet long makes a complete revolution under a force of 2 tons acting tangentially to the path of the crank pin. What pressure must act constantly on each square inch of a piston, 3 feet in diameter, and moving through a stroke of 4 feet, in order that the work done on the piston may be equal to that done on the crank pin? (1874.)

61. Will you state clearly the points which determine the energy of any fly-wheel, and show by an example how the energy of a fly-wheel would be affected—1st, by doubling the weight; 2nd, by doubling the diameter, the weight and number of revolutions remaining the same; and 3rd, by doubling the number of revolutions in a given time? (1873.)

62. Sketch the ordinary pendulum or ball governor of a steam engine. Mark on your drawing some particular line whose length is related to the number of revolutions of the balls. State the relation as nearly as you know it. If the line referred to be shortened in the proportion of 2 : 3, how much would the number of revolutions be increased? (1876.)

63. Given the breaking tensile strain of wrought iron, find the thickness of the shell of a cylindrical boiler which will support a given pressure of steam. Example.—The diameter of the shell is $3\frac{1}{2}$ feet, and the pressure of the steam is 150 lbs. on the square inch, what should be the thickness of the boiler plate when the tensile strain of wrought iron is, *for safety*, estimated at 3 tons on the square inch? Prove that a tube under internal fluid pressure is twice as strong on a transverse as on a longitudinal section. (1875.)

64. A steam engine of the overhead beam construction is employed in working a cylinder for blowing air; the steam cylinder at one end of the beam is 8 feet from the fulcrum, and the blowing cylinder is at the other end, but is twice the distance, namely, 16 feet from the centre of motion of the beam. The area of the steam piston is 1,000 square inches, with a uniform pressure of 40 lbs. per inch. The question is, what average pressure could be exerted by the blowing piston, its area being double that of the other? (1868.)

65. Water is pumped from a well 400 feet deep by a single-acting inverted steam engine; that is to say, the piston rod is downwards, and steam is admitted under the piston for the up-stroke only, the downward motion being left to gravitation. The piston rod gives motion to a lever 15 feet from the fulcrum or centre of motion, but the lever is carried out to 20 feet, and then the pump rod is attached; there is thus 5 feet between the pump and engine centres, and 15 feet to the fulcrum centre. The steam pressure on piston is 50,000 lbs., and the question is, what force will be exerted on the pump rod during the upward stroke?

Referring to the former part of the question, the steam under piston would have the piston, beam, and pump rods to lift in addition to the water, but the lifting of those parts is not lost, because it can be made to raise nearly an equal weight of water during their descent; will you explain how this can be done, state the kind of pump that you would employ, where you would introduce air-vessels, and the disadvantage that would arise from their omission? (1868)

ANSWERS TO SOME OF THE ABOVE EXAMPLES.

3.—15·98 lbs.
4.—100,800,000 ft. lbs.
6.—$\frac{1}{8}$ J.H.
9.—H.P. = 51·1
11.—21·372 lbs.
13.—122·79 F.
14.—$\begin{cases} 2·8 \\ 26·965 \end{cases}$
17.—7·746 inches.
18.—55 inches.
20.—9·44 inches.
21.—26703·6 lbs.
22.—·06 inch.
23.—9·337 ft. per sec.
25.—1·23 inch.
28.—858·9 lbs.
32.—$\frac{1}{4}$ (travel of slide).
34.—$\begin{cases} 123131·17 \text{ lbs.} \\ 81048·37 \text{ lbs.} \end{cases}$
35.—11° 12′ 44″.
36.—load = 17·8755 lbs.
38.—4·7124 lbs.
42.—$\begin{cases} 18\frac{63}{64} \text{ lbs.} \\ 380·35 \end{cases}$
44.—2·5465
47.—$\frac{A}{2}$.
48.—218061 ft. lbs.
49.—$\begin{cases} 153192 \text{ ft. lbs.} \\ 43·1 \text{ inches.} \end{cases}$
52.—46·3.
55.—8593·857 ft. lbs.
56.—$\begin{cases} 11·4977442 \text{ lbs.} \\ ·44 \text{ cub. ft.} \end{cases}$
59.—7264160·156 ft. lbs.
60.—6·91 lbs.

ADDITIONAL EXAMPLES.

Science Exam. 1879.

1. The cylinder of an engine is 25 inches long, and steam is admitted at 18 lbs. actual pressure, the final pressure being 4 lbs. At what point of the stroke was the steam cut off?

   Ans. $5\frac{5}{9}$ inches from beginning of stroke.

2. In a steam engine the diameter of the steam cylinder is 50 inches, the length of stroke is 7 feet, the number of revolutions is 25 per minute, and the mean effective pressure of the steam is 11·3 lbs. Find the horse-power of the engine. *Ans.* H.P. = 235·3.

3. Required the weight to be placed on the end of a safety valve lever $17\frac{1}{2}$ inches long, the distance from the fulcrum to the valve being $3\frac{1}{2}$ inches, the upward pressure on the valve required for lifting the valve and lever being 20 lbs., and the pressure of steam in the boiler being 100 lbs. per square inch above that of the atmosphere.

   Ans. $W = 20A - 4$, where A is the area of the valve in square inches.

4. The cylinder of an engine is 25 inches long; steam is admitted at 18 lbs. actual pressure, and the final pressure is 4 lbs. Dividing the stroke into 10 equal parts, find the steam pressure at each point of division, and set out Watt's diagram of work done. Find also the mean pressure of the steam.

   Ans. 18, 18, $13\frac{1}{3}$, 10, 8, $6\frac{2}{3}$, $5\frac{5}{7}$, 5, $4\frac{4}{9}$, 4. Mean pressure = $10\frac{1}{63}$ lbs.

Science Exam. 1880.

1. What is the latent heat of steam? If a quantity of steam weighing one pound, and at a temperature of 220° F., is condensed in 100 lbs. of water at 60° F., what is the resulting temperature?

   Ans. 71°·1 F.

2. The stroke of the piston in a direct-acting engine is 4 feet, and the length of the connecting rod is 9 feet. How far is the piston

from the middle of its stroke when the crank has made $\frac{1}{4}$ of a revolution from a dead point? *Ans.* 2·7 inches.

3. An engine is using steam at 21 lbs. pressure per square inch above the atmosphere, the length of the stroke is 3 feet, and the steam is cut off at one third of the stroke. Set out in a diagram the approximate steam pressure on one side of the piston throughout the stroke, and mark the pressures at the second and third feet of the stroke. *Ans.* 18 lbs.; 12 lbs.

4. In a double-acting engine the mean pressure on the piston is 4 tons, and the length of stroke is 18 inches. What is the mean tangential driving pressure which can be taken from the rim of the fly wheel, the estimated diameter of which is 8 feet?

   Ans. 1069·1 lbs.

5. What is the speed of the piston of a locomotive engine having 24 inches stroke, with 7 feet driving wheels, and running at 40 miles per hour? *Ans.* $10\frac{2}{3}$ feet per second.

6. The diameter of a safety valve is $2\frac{1}{2}$ inches, and the leverage is 5 to 1. What is the pressure of the steam when the pull at the end of the lever is 100 lbs.? *Ans.* 101·86 lbs. per sq. inch.

7. The cylinders of a locomotive engine are 17 inches in diameter and the length of stroke is 24 inches, also the driving wheel makes 100 revolutions per minute, and the mean effective pressure of the steam is 80 lbs. Find the horse-power.

   Ans. H.P. = 440·2.

8. Find the pressure of steam necessary for blowing out a boiler 10 feet below the level of the sea, the weight of a cubic foot of salt water being taken at 64 lbs.

   Ans. $4\frac{4}{9}$ lbs. per sq. inch above the atmosphere.

9. In a direct-acting engine find the ratio of the velocity of the crank-pin to that of the piston in any given position of the crank.

10. A non-condensing engine is using steam at 42 lbs. pressure per square inch above the atmosphere, the length of the stroke is 3 feet, and the steam is cut off at $\frac{1}{3}$ of the stroke. Find the mean pressure of the steam.

    Ans. Theoretical mean pressure = 24·87 lbs.

11. Explain the operation of combining the indicator diagrams of work done in a compound cylinder engine, the object being to produce the diagram which would have been obtained if the steam had performed the same work by going through the same changes of pressure and volume in one cylinder.

Science Exam. 1881.

1. Describe a double-beat or equilibrium valve. The upper side of the valve is 11 inches in diameter, and the lower side $10\frac{1}{2}$ inches. What power will be required to open it when the steam has a pressure of 10 lbs. above the atmosphere, the pressure between the valves being disregarded? *Ans.* 211 lbs.
2. The stroke of a piston is 4 ft. 6 in., the steam is cut off at 9 inches, and the pressure at the end of the stroke is 5 lbs. below that of the atmosphere. At what pressure above the atmosphere was the steam admitted? *Ans.* 45 lbs.
3. How is a barometer gauge made and fitted? If the mercury in an ordinary barometer stands at 30 inches when that in the gauge stands at 26 inches, find the pressure per square inch of the vapour or air in the condenser. *Ans.* 2 lbs.
4. The cylinder of a single-acting pumping engine is 72 inches in diameter with a stroke of 10 feet, and it works a pump whose plunger is 23 inches in diameter with a stroke also of 10 feet. The load is 142 lbs. per square inch of the area of the plunger. Find the mean pressure of the steam per square inch of the piston, and the horse-power when the engine makes 8 strokes per minute. *Ans.* Mean pressure = 14·49 lbs. H.P. = 143.
5. An ordinary cylindrical boiler has flat ends with two internal flues running from end to end. The boiler is 28 feet long, the shell 7 feet in diameter, and each of the two flues is 30 inches in diameter, the iron employed being $\frac{1}{2}$ inch in thickness throughout. Taking the ultimate strength for the longitudinal or double-riveted joints at 35,000 lbs. per square inch of sectional area, and that for the transverse or single-riveted joints at 28,000 lbs. per square inch, find the ultimate bursting pressure (1) along a longitudinal; (2) along a transverse section. In what way are the internal flues strengthened?

Ans. (1) $416\dot{6}$ lbs. per sq. inch.
(2) 1534·2 lbs. per sq. inch.

Science Exam. 1882.

1. What effect is produced by putting lap on a slide-valve? The lap on the steam side of a slide-valve is $1\frac{1}{2}$ inches, that on the exhaust side is $\frac{1}{4}$ inch, and the lead is $\frac{1}{8}$ inch. Find the opening for exhaust which the valve will give at the lower port when the piston is at the top of its stroke. *Ans.* $1\frac{3}{8}$ inch.

2. State the law according to which the pressure of a mass of air diminishes as its volume increases, the temperature being unchanged. Assuming this law to hold for the expansion of steam, find the steam pressure at the end of the stroke of the piston in an engine where the steam is admitted at a pressure of 30 lbs. above the atmosphere and is cut off at $\frac{2}{5}$ths of the stroke.

   Ans. 3 lbs. above the atmosphere.

3. The area of the piston of an engine is 3 sq. feet, the pressure of the steam is 15 lbs. per square inch above the atmosphere on admission, and the steam is cut off at $\frac{1}{3}$ of the stroke; the crank shaft makes 40 revolutions per minute, and the length of the stroke is three feet, find the H.P. (given hyp. log. $3 = 1 \cdot 0986$).

   Ans. H.P. $= 65 \cdot 9$.

4. An engine is competent to raise 70 millions of pounds through one foot by the burning of 112 lbs. of coal. How many pounds of coal does it consume per horse-power per hour? *Ans.* $3 \cdot 168$.

5. Find the number of cubic feet of water required per H.P. per hour in a non-expanding non-condensing engine, the pressure of the steam on the piston throughout the stroke being taken at 15 lbs. above the atmosphere, and the volume of steam at that pressure being taken at 874 times the volume of the water from which it is generated. *Ans.* $1 \cdot 05$.

6. A mass of air at atmospheric pressure is compressed by the action of an engine and is heated thereby. It is afterwards cooled down to its original temperature before compression, and is then expanded while doing work. When it again arrives at the pressure of the atmosphere it is intensely cold and may be used for refrigerating purposes. Explain these results according to the principles of Thermo-dynamics. Why is it an advantage to cause the air to do work while expanding?

Science Exam. 1883.

1. In a beam engine the mean pressure of the steam on the piston is 20 tons, and the length of the crank is $2\frac{1}{2}$ feet, what is the horse-power when the crank shaft makes 30 revolutions per minute?

   Ans. H.P. $= 407\frac{3}{11}$.

2. In a jet condenser the temperature of the condensing water is 60° and that of the entering steam is 212°. Also the condenser remains at a temperature of 104°. Under these conditions find the weight of condensing water per pound of steam which enters the condenser. *Ans.* $24 \cdot 4$ lbs.

3. Define the horse-power of an engine. If an engine consumes 2 lbs. of coal per horse-power per hour, how many foot-pounds of work will it perform when consuming 112 lbs. of coal?

   What diameter of cylinder will develop 50 horse-power with a four-foot stroke, 40 revolutions per minute, and a mean effective steam pressure of 30 lbs. above the atmosphere, the engine being non-condensing?

   Ans. 110,880,000 ft. lbs.; diameter = 14·8 inches.

4. Explain the method of constructing a parallel motion for a compound cylinder beam engine.

5. Show that no more work is obtained from a given quantity of steam by passing it through two cylinders as in a compound engine than by admitting it into a low-pressure cylinder only with the same degree of expansion.

6. In a direct-acting engine, set out by a diagram the relative positions of the piston and crank during a stroke on the supposition that the connecting rod is of infinite length or remains parallel to itself. How is this diagram altered when a definite length is assigned to the connecting rod?

Science Exam. 1884.

1. Define the horse-power of an engine. Find the horse-power of a locomotive engine which can draw a train weighing 100 tons (including its own weight) along a level road at 30 miles per hour, the train resistance being taken at 10 lbs. per ton of load.

   Ans. H.P. = 80.

2. Steam is admitted into the cylinder of an engine at an actual pressure of 45 lbs. per square inch, and is cut off at one-third of the stroke. Find the pressure in pounds at half-stroke, and also at the end of the stroke. *Ans.* 30 lbs.; 15 lbs.

3. Describe a mercurial pressure gauge for indicating the pressure of steam in a boiler. If the specific gravity of mercury be 13·5, how much higher will the mercury stand in one leg than in the other when the pressure of the steam is 10 lbs. on the square inch above the atmospheric pressure. *Ans.* 20·5 inches nearly.

4. In a condensing engine the back pressure is 4 lbs. per square inch on the piston, and the actual pressure of steam in the steam chest is 30 lbs. per square inch. If the clearance between the piston and the inside of the cylinder cover be $\frac{1}{2}$ inch, how far must the piston be from the end of the stroke at the point of

compression in order to compress the vapour in the cylinder to the pressure of the steam in the steam chest?

Ans. $3\frac{1}{4}$ inches from end of stroke.

5. If 2 lbs. of steam at 212° F. are passed into 30 lbs. of water at 70° F., what is the temperature of the water at the end of the operation? *Ans.* 139°·28.
6. Find the greatest diameter of a cylindrical boiler to resist a pressure of 100 lbs. per square inch, the plates being $\frac{3}{8}$ inch thick, and the safe stress upon the metal being 5,500 lbs. per square inch. *Ans.* $41\frac{1}{4}$ inches.
7. Steam is admitted to a cylinder at a pressure of 80 lbs. to the inch, and is cut off at one-third of the stroke. The diameter of the piston is 40 inches and the length of stroke 5 feet, the number of revolutions being 50 per minute. Given hyp. log. 3 = 1·0986, find the horse-power of the engine. *Ans.* $1{,}066\frac{3}{8}$ H.P.

Science Exam. 1885.

1. If 400 tons be lifted 10 feet in 10 minutes by a steam engine, wherein the area of the piston is 400 square inches, the mean pressure of the steam on the piston is 25 lbs. on the square inch, the length of stroke is 4 feet, and the number of double strokes made in a minute is 15: what proportion of the power applied to the piston is lost in the working of the machinery?

   Ans. $25\frac{1}{3}$ per cent.
2. Steam is admitted into a cylinder at a pressure of 25 lbs. on the square inch above the atmospheric pressure of 15 lbs. on the square inch, and is cut off at such a point that its pressure at the end of the stroke is 5 lbs. below that of the atmosphere. At what point of stroke was it cut off? Make a diagram, showing approximately the steam pressure on the piston throughout the stroke. *Ans.* Cut off at $\frac{1}{4}$ stroke.
3. Steam is admitted into a cylinder 32 inches long at 40 lbs. pressure above that of the atmosphere (viz. 15 lbs. on the square inch), and is cut off at one-fifth of the stroke. The area of the piston being 3 square feet, find the work done in one stroke by dividing the stroke into five equal parts and considering the pressure in each of the latter four parts to be the mean of the pressures at the beginning and end of the same.

   Ans. 34002·432 foot-pounds.
4. If the boiler of an engine gives out every minute 100 cubic feet

of steam which propels the piston with an average pressure of 50 lbs. on the square inch, what is the horse-power of the engine? *Ans.* H.P. = 21 [illegible]/11.

5. In a direct-acting horizontal engine the length of the crank is 1 foot, and that of the connecting rod is 5 feet. When the crank is vertical the pressure of the steam on the piston is 4,000 lbs.; find the thrust along the connecting rod, and the pressure on the guide bars at that point of the stroke.

Ans. Thrust = 4082·48 lbs.
Pressure = 816·496 lbs.

6. If the cylinder of a locomotive be 20 inches in diameter with a stroke of 2 feet, and the diameter of the driving wheel be 6 feet, find the tractive force exerted by the engine for each pound of pressure per square inch on the piston. *Ans.* $66\frac{2}{3}$ lbs.

7. It being given that the travel of a slide valve is $4\frac{1}{2}$ inches, the outside lap 1 inch, the inside lap $\frac{1}{4}$ inch, and the angle of advance of the eccentric 30°, find (on the assumption that the obliquity of the eccentric bar or rod may be neglected) the positions of the crank at admission, cut off, release, and compression.

Ans. $3^\circ\ 36\frac{3}{4}'$, $56^\circ\ 23\frac{1}{4}'$, $23^\circ\ 37\frac{1}{4}'$, $36^\circ\ 22\frac{3}{4}'$; the angles being measured from the line of dead centres.

8. In a compound cylinder tandem engine the steam is cut off at one-third of the stroke in the high pressure cylinder, the areas of the pistons are as 1 to 3, and the diameter of the smaller cylinder is 20 inches; investigate an expression for the work done in one stroke. Example: Find the horse-power of the engine when the initial pressure of the steam is 85 lbs. per square inch above that of the atmosphere—viz. 15 lbs., the back pressure in the large cylinder is 3 lbs. per square inch, and the speed of each piston is 300 feet per minute. Given that hyp. log. 3 = 1·0986.

Ans. H.P. = 278·66.

Science Exam. 1886.

1. Explain the advantage of working steam expansively and with condensation. Steam is admitted into a cylinder at 30 lbs. above the atmosphere, which is taken at 15 lbs. per square inch, and is cut off at a certain point and then expands to a pressure of 5 lbs. below the atmosphere. If the length of stroke be $4\frac{1}{2}$ feet, at what point is the steam cut off?

Ans. At $\frac{2}{9}$ths of stroke.

2. In a jet condenser the temperature of the injection water is 60° F.,

that of the water after condensation is 100° F., and the latent heat of the steam which enters the condenser is 1,016 thermal units, the temperature of the steam being then 140° F.; find the number of pounds of injection water for each pound of steam condensed. *Ans.* 26·4 lbs.

3. The diameter of the cylinder of an engine being 53 inches, the stroke 5 feet, and the number of revolutions 30 per minute, find the mean pressure of the steam to develop 600 indicated horse-power. *Ans.* 29·9 lbs., taking $\pi = \frac{22}{7}$.

4. Find the thickness of iron plates in a boiler shell 6 feet 4 inches in diameter for a pressure of 40 lbs., the greatest tensile stress permissible in the material being 5,000 lbs. per square inch. *Ans.* ·304 inches.

5. Given that the travel of a slide valve is 5 inches, outside or steam lap $\frac{3}{4}$ inch, and the angle of advance $22\frac{1}{2}$°, find graphically, or otherwise, the position of the crank at the point of cut-off. *Ans.* 140° 2′ from the line of dead centres.

6. A motion of 1 inch in the pencil of an indicator, as due to steam pressure, represents a pressure of 20 lbs. on the square inch. What is the H.P. of an engine, making 90 revolutions per minute, the diameter of the piston being 10 inches, the length of stroke 20 inches, the area of the indicator diagram 8 square inches, and its length 5 inches? *Ans.* 22·848, taking $\pi = 3·1416$.

7. An engine uses 10 lbs. of steam per minute, the feed temperature is 60° F., the boiler temperature 300° F., and that of the condenser is 104° F. What is the theoretical maximum efficiency of the engine? State Regnault's formula for the total heat of steam at a given temperature, and deduce the amount of heat which each pound of steam has received in the boiler. What horse-power would be developed if the engine worked as a perfect engine? *Ans.* Max. efficiency = ·258; H.P. = 69·135.

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